VOLCANIC HAZARD RISK ASSESSMENT FOR THE RISKSCAPE PROGRAM, WITH TEST APPLICATION IN ROTORUA, NEW ZEALAND, AND MAMMOTH LAKES, USA.

A thesis submitted in partial fulfilment of the
requirements for the Degree
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ABSTRACT

This thesis presents a new GIS-based scenario volcanic risk assessment model called RiskScape Volcano (RSV) that has been designed for the RiskScape program to advance the field of volcanic risk assessment. RiskScape is a natural hazards risk assessment software tool being developed in New Zealand by GNS Science and NIWA. When integrated into RiskScape, RSV will add proximal volcanic hazard risk assessment capability, and enhanced inventory design; it presently operates outside of RiskScape by combining volcanic hazard models' output spatial hazard intensity (hazard maps) with inventory databases (asset maps) in GIS software to determine hazard exposure, which is then combined with fragility functions (relationships between hazard intensity and expected damage ratios) to estimate risk. This thesis consists of seven publications, each of which comprises a part of the development and testing of RSV: 1) results of field investigation of impacts to agriculture and infrastructure of the 2006 eruption of Merapi Volcano, Indonesia; 2) agricultural fragility functions for tephra damage in New Zealand based on the observations made at Merapi; 3) examination of wind patterns above the central North Island, New Zealand for better modeling of tephra dispersal with the ASHFALL model; 4) a description of the design, components, background, and an example application of the RSV model; 5) test of RSV via a risk assessment of population, agriculture, and infrastructure in the Rotorua District from a rhyolite eruption at the Okataina Volcanic Centre; 6) test of RSV via a comparison of risk to critical infrastructure in Mammoth Lakes, California from an eruption at Mammoth Mountain volcano versus an eruption from the Inyo craters; and 7) a survey of volcanic hazard awareness in the tourism sector in Mammoth Lakes. Tests of the model have demonstrated that it is capable of providing valid and useful risk assessments that can be used by local government and emergency management to prioritise eruption response planning and risk mitigation efforts. RSV has provided the RiskScape design team with a more complete quantitative volcanic risk assessment model that can be integrated into RiskScape and used in New Zealand and potentially overseas.

Te Puia Geothermal Area, Rotorua, dusk, October 2005

ACKNOWLEDGMENTS

I would like to thank Prof. Jim Cole for taking me on as a student at the University of Canterbury and assisting me with the establishment of this project, as well as Andrew King of GNS Science for allowing me to join the RiskScape team. Peter Brownbridge at the Rotorua District Council graciously showed me the urban geothermal features of Rotorua and provided my project with GIS data for that beautiful town. I would like to thank the University of Canterbury Doctoral Research Scholarship and the New Zealand International Doctoral Research Scholarship for funding my PhD. I would also like to thank Ms. Tracey Fuller of Mammoth Lakes for hosting our science team at her home in 2006, as well as Brian Barnock for providing me with lodging in Mammoth in 2007. The Mono County GIS office provided the GIS data of Mammoth Lakes, for which I am grateful. Sutikno Bronto, Sri Mulyaningseh, and her husband Suehartono hosted me with the utmost of hospitality in Yogyakarta, Indonesia in 2006, and for their friendship I will forever be grateful. Jim Cousins, Warwick Smith, and Chris Massey of GNS Science all provided much assistance to me via editing and/or technical discussions. Robin Pringle at GNS aided me with updating the EXPLORIS software, and none of the pyroclastic density current modeling could have taken place without his help. I could not have accomplished any of the work in this thesis without the guidance and assistance of Dr. David Johnston, of the Massey University Joint Centre for Disaster Research and GNS Science. Also, Tom Wilson of the University of Canterbury provided me with many useful discussions, and I am grateful for the chance to have worked with him. Penny Murray, Daryl Barton, and Jan Bushby, all of GNS Science, assisted me with the preparation of the science reports that comprise this thesis, and for their help I an indebted. Sally Kaye, also provided copy editing, and for her help I am grateful. Frank Trusdell of the USGS Hawaiian Volcano Observatory hosted me in his home when I visited HVO in 2006, after having encouraged me to study towards a PhD in the first place in 2004. Dr. Richard Roscoe (http://photovolcanica.com) graciously provided photographs that I used to depict volcanic damage, and for his help I am grateful. Eric Hudock allowed me to finish editing this thesis, and I am grateful for his lenience. Finally and most importantly, I would like to thank Dr. Kirsten Finnis for…..everything.

ABBREVIATIONS/GLOSSARY

1. GNS Science = Geological and Nuclear Sciences New Zealand
2. NIWA = National Institute of Water and Atmospheric Research
3. RSV = RiskScape Volcano
4. PDC = Pyroclastic density current
5. GIS = Geographic Information Systems
6. OVC = Okataina Volcanic Centre
7. AVF = Auckland Volcanic Field
8. TVZ = Taupo Volcanic Zone
9. ALOHA = Areal Location of Hazardous Atmospheres model
10. EXPLORIS = Explosive eruption risk and decision support for European Union populations threatened by volcanoes
11. MCDEM = New Zealand Ministry of Civil Defence and Emergency Management
12. D.R.E = Dense Rock Equivalent

1. INTRODUCTION

Volcanic risk assessment is the examination of the risk posed to the human, natural, or built environments as a result of damaging volcanic activity, and is typically done before the damaging activity takes place. Humans have a long and often tragic history of building large civilisations in close proximity to dangerous volcanoes, partly due to the vast amounts of fertile arable land that typically ring them. Volcanoes are not inherently hazardous unless people choose to live and build their societies in harm's way. As long as humans continue to settle in the shadow of volcanoes, we should continue to develop technological tools to aid us in understanding the volcanic risks we face and advance our ability to mitigate them.

In New Zealand, where volcanic risk is elevated due to a relative abundance of hazardous volcanoes, a joint effort between GNS Science and NIWA has been underway since 2005 (King and Bell, 2005; Reese et al., 2007a and 2007b) to create a new software tool for natural hazards risk assessment, called "RiskScape." Like the HAZUS program in the USA (FEMA, 2003) on which it was initially based, RiskScape combines natural hazard models and their output spatial description of hazard intensity (hazard maps) with inventory databases (asset maps), and inventory vulnerability estimates (fragility functions) to estimate exposure and risk from natural hazards. RiskScape is a GIS-like program written in the Java software language.

As of early 2008, RiskScape is still under development (A. King, GNS Science, *pers. comm.*, 2008) as a custom-engineered Java-based software program. RiskScape presently has the capability to estimate risk to limited building inventory from earthquakes and river floods in Westport and Christchurch on the South Island, and earthquakes, floods, and volcanic tephra in the Hawke's Bay on the North Island. It does not yet have full functionality, and many decisions about the ways in which it operates, appears, and models risk from natural hazards remain to be made by its developers.

To assist in the development of RiskScape, a new and separate model for volcanic risk assessment was created, called "RiskScape Volcano" or RSV. When combined, RSV will upgrade the capability of RiskScape to include additional volcanic hazards models that consider proximal hazards as well as distal hazards. RSV also adds new fragility functions, additional asset/inventory databases, and definitions that can be used to construct new inventory databases for other locations other than the test locations mentioned above.

This thesis presents seven different publications, each of which represent different aspects of the effort to create and test the RiskScape Volcano model. The next section will describe the publications, and how they fit into the overall body of the thesis.

1.1 Format of Thesis and List of Original Publications

This thesis consists of two distinct portions as a result of it being primarily composed of seven publications: a first half which contains the main chapters of the thesis itself (Chapters 1-9); and a second half which contains reproductions of the publications (Chapters 10-16). The format of the thesis is based on the dissertation of Schmidt-Thomé (2006), which consists half of publications and half of summary text and discussion.

The thesis begins with Chapter 1, which provides an introduction to the concepts and scope of the thesis as a whole. RiskScape and RiskScape Volcano will be introduced, along with a review of volcanic risk assessment methodologies, and relevant recent and historical efforts made in the field of volcanic risk assessment in New Zealand. A comparison of RiskScape to similar overseas efforts HAZUS and EXPLORIS (EXPLORIS Consortium, 2005) is also provided. Chapter 2 follows with a description of the thesis' overall research questions and goals. The next two chapters (3 and 4) detail the geologic background of the two locations used to test the RiskScape Volcano model – Rotorua and the Okataina Volcanic Centre in New Zealand, and Mammoth Lakes, California, and the Long Valley Caldera in the USA. These geologic background chapters are followed by a discussion (Chapter 5) that provides a dialogue of overarching topics relevant to the thesis as a whole, including a discussion of issues involved with integrating the RiskScape Volcano model into the RiskScape software. In a similar manner in Chapter 6, the main conclusions of the thesis will be summarised via a review of the answers to the research questions posed in Chapter 2. Chapter 7 provides the references cited in the first 7 chapters of the thesis. Each publication then lists its own references.

The second half of the thesis (Chapters 8-14) consists of reproductions of all seven publications, which are numbered Publications I-VII as outlined in Table 1.1, and are presented exactly as originally published. Six of the publications are internally peer-reviewed GNS Science reports published by GNS Science in New Zealand in 2007 and 2008 (Publications I-V and VII). Publications VI is a manuscripts that has been accepted for publication by the journal *Natural Hazards* on 24 October 2008. The earlier publications were joint efforts, while the later papers are not. For those publications where the author of the thesis is not the first author, a description of the specific contribution of the thesis' author will be given prior to that publication's chapter. Where errors have been found in the publications during thesis examination, corrections and addendums are given in the thesis text at the beginning of the chapter introducing that publication.

Throughout the first half of the thesis, effort will be made to detail how the publications refer and relate to each other in the context of the overall thesis, using the Roman numerals given in Table 1.1.

Chapter No.	Publication No.	Title	Published in/as	Authors (in order)	Pages
8	I	Impacts of the 2006 eruption of Merapi volcano on agriculture and infrastructure	GNS Science Report (2007/07)	Tom Wilson, Grant Kaye, Carol Stewart, and Jim Cole	64
9	II	Agricultural fragility estimates for volcanic ash fall hazards	GNS Science Report (2007/37)	Tom Wilson, Grant Kaye	51
10	III	Examining wind patterns above the central North Island for tephra dispersion modeling with ASHFALL in RiskScape	GNS Science Report (2007/36)	Grant Kaye	41
11	IV	RiskScape Volcano – a volcanic hazard risk assessment model for RiskScape	GNS Science Report (2007/38)	Grant Kaye	176
12	V	Risk assessment of population, agriculture, and infrastructure in the Rotorua District from a rhyolite eruption at the Okataina Volcanic Centre, New Zealand	GNS Science Report (2007/39)	Grant Kaye	62
13	VI	Comparison of pyroclastic density current hazard risk to critical infrastructure in Mammoth Lakes, California, USA from a new Inyo craters rhyolite dike eruption versus a dacitic dome eruption on Mammoth Mountain	*Natural Hazards*, submitted	Grant Kaye, Jim Cole, Andrew King, David Johnston	30
14	VII	Mammoth Lakes Business Survey	*GNS Science Report* *(2008/35)*	Grant Kaye, Kirsten Finnis, David Johnston, Douglas Paton	10

Table 1.1 Publications reproduced within the thesis.

Note that the Table of Contents of the thesis refers only to Chapters 1-7, and each of the following chapters (publications) has its own table of contents and sequential page numbers. Basic introductions and definitions of volcanic risk assessment terms and concepts found in the publications are not repeated here in an effort to avoid redundancy.

1.2 Review of Volcanic Risk Assessment Methodologies

Volcanic risk assessment methodologies follow the same basic set of steps:

1. Study the volcano's past behaviour (hazardscape) in order to determine what could potentially happen there in the future, particularly:
    a. what volcanic hazards have occurred there in the past
    b. where on and around the volcano they have occurred
    c. with what magnitude they have occurred
    d. in what duration and time scale have they occurred
2. Use modeling techniques in the context of #1 to craft eruption scenarios of theoretical future activity
3. Map the potential scenarios as hazard maps showing the spatial distribution and intensity of hazardous conditions
4. Gather information about what is at risk on and around the volcano from future activity (inventory maps)
5. Understand how the inventory is vulnerable to the activity (fragility functions).

All of these concepts are defined and described in more detail in Publication IV, as they relate to the RiskScape Volcano risk assessment model. An optional, sixth step, forecasting the likelihood of loss in probabilistic terms, is a further extension of volcanic risk assessment methodology that is being increasingly utilised (e.g EXPLORIS program, see Baxter et al., 2008 *in press*), and will be discussed below. Probabilistic risk assessment is not undertaken in this thesis.

Volcanic risk assessment methodologies are here reviewed in two different categories: deterministic, scenario-based risk assessment efforts that focus on understanding the implications of hypothetical eruption scenarios to the human, built and natural environments (inventory), but fall short of quantifying the likelihood of those scenarios; and probabilistic risk assessment methodologies that seek to quantify the impacts of possible eruptive activity to inventory in terms of their likelihood and return period. It is worth noting that scenario-based risk assessment results commonly form a foundation for probabilistic risk assessments, in a sense that any understanding of probable future activity at a volcano must be based on a grasp of what has happened in the past (Baxter et al., 2008 *in press*).

1.2.1 Scenario-Based Risk Assessment Methodologies

1.2.1.1 Geologic and Hazard Mapping

One of the most common and fundamental methods of scenario-based volcanic risk assessment efforts is geologic mapping, which is done in order to establish the types and locations of past activity at a volcano (e.g. Figure 1.1, map of lava flows at Mauna Loa volcano, Hawai`i). This facilitates drafting hazard maps of potential future activity and the dangerous zones created around the volcano. This mapping must be done in concert with careful studies of the rocks and deposits, in order to characterise them properly in terms of composition, provenance, and age dating. This falls under step 1, above.

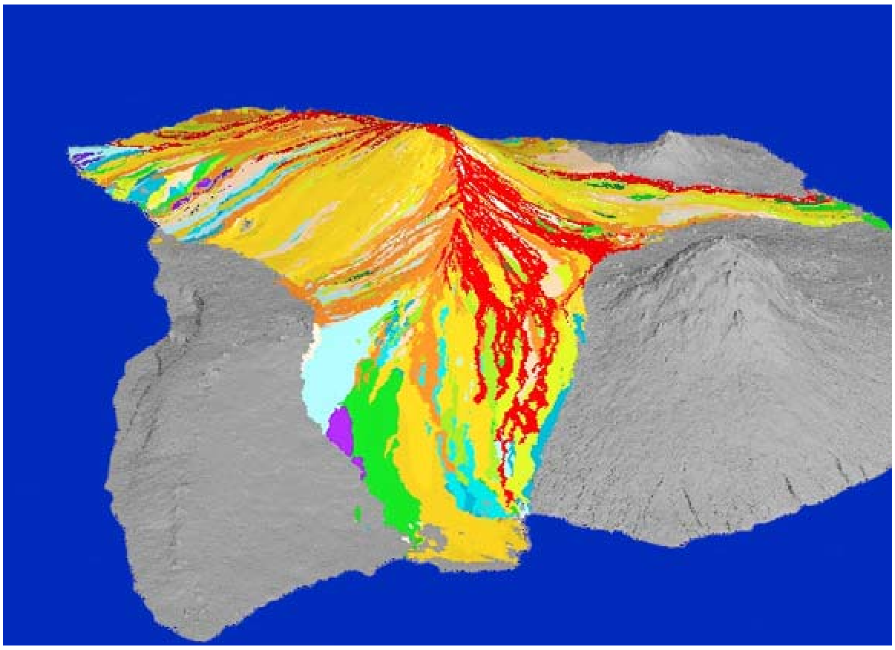

Figure 1.1 Map of surface lava flows younger than 1832 from Mauna Loa Volcano, from Trusdell et al., 2002.

An understanding of the past history of a volcano can be easily translated into a hazard map, if the areas where past volcanic activity has occurred can be taken to represent the locations where future activity is likely to occur. Figure 1.2 shows a volcanic hazard map delineating potential inundation zones from eruptions on the southwest rift zone of Mauna Loa, which was based on geologic maps such as that shown in Figure 1.1.

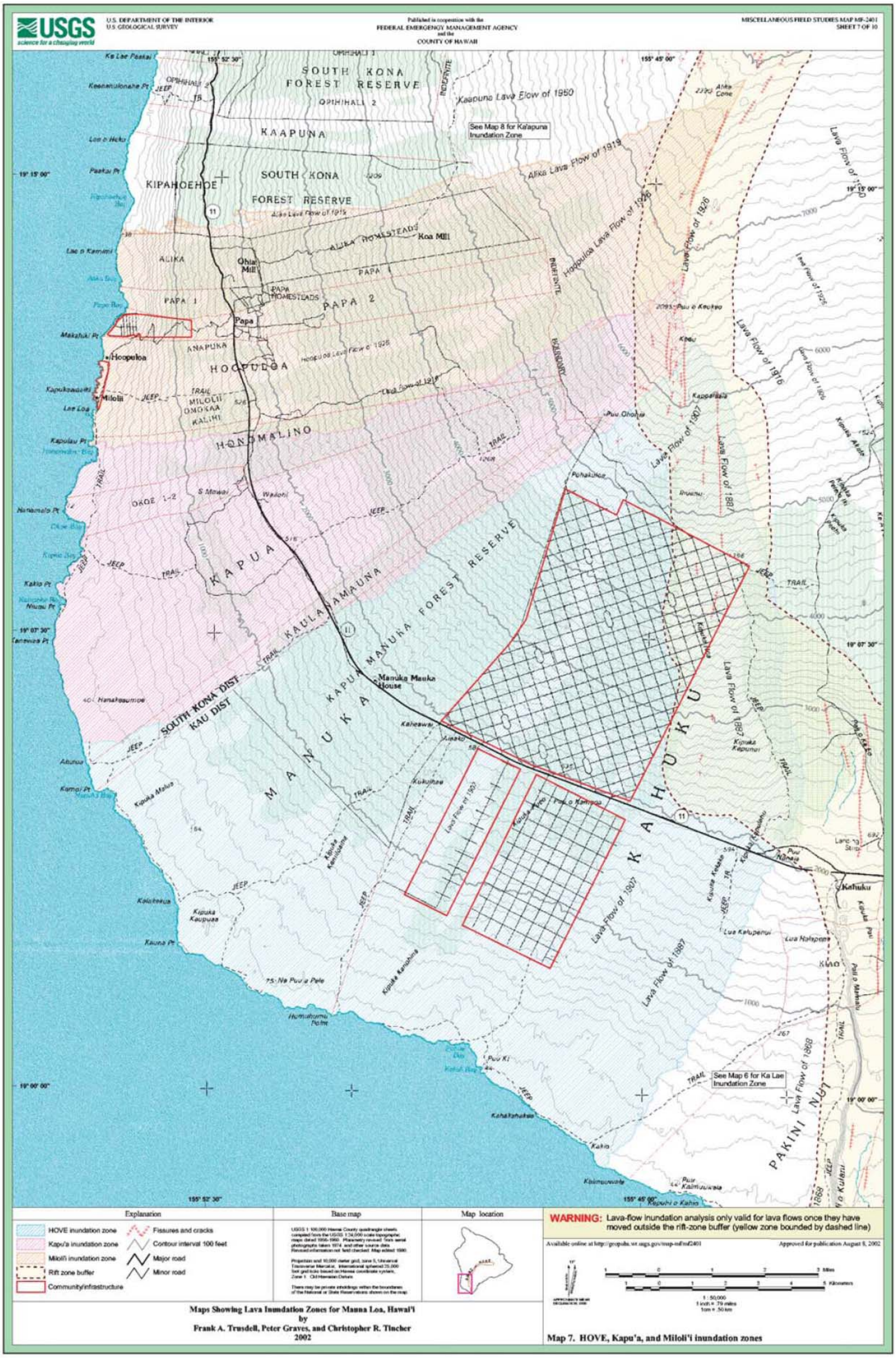

Figure 1.2 Lava flow inundation zones for Mauna Loa, from Trusdell et al., 2002.

Figure 1.2 was produced with GIS modeling software, and is an example of steps 2 and 3 of the generic risk assessment methodologies listed above. Inventory data such as subdivisions (red boxes) and roads (thick black lines) is also shown on the map, providing an example of step 4 of the risk assessment methodology described above. This hazard map shows the possible risk to the inventory, because it lies within likely inundation zones – it does not quantify the risk to inventory; it merely shows it as being *at risk*. Questions remain as to how the inventory is vulnerable to the hazards, i.e. how in this case would lava flows cause damage to roads or houses? These questions would be answered via vulnerability or fragility functions (step 5, above) relating damage to hazard intensity. Numerous examples and a more detailed description of the above scenario-based risk assessment methodologies are found throughout the thesis in the various publications, in particular Publication IV, V and VI.

1.2.1.2 Computer and GIS-based Risk Assessment

In recent times, computer simulations such as that used to produce Figure 1.2 provide researchers with powerful tools with which to create eruption scenarios for risk assessment, and even to progress through the five (or six) steps given above in section 1.2 in one software environment. Geographic Information Systems (GIS) provides such a means to combine hazards maps and inventory maps to determine volcanic risk in regions around volcanoes (e.g. Carrarra et al., 1995; Coppock, 1995; Kauahikaua et al., 1995; Pareschi, 2000; Trusdell et al., 2002; Pareschi, 2002; Leung et al., 2003; Gaspar et al., 2004; Cole et al., 2005a; Spence et al., 2005a and 2005b; Theirry et al., 2008). Spatial analytical techniques inherent to GIS provide an easy and rapid means of determining hazard exposure, while simultaneously being able to query large inventory databases that can be contained within maps, holding vast amounts of inventory attribute information. RiskScape and HAZUS provide examples of all-encompassing GIS-based volcanic risk assessment engines; both will be discussed in greater detail in this thesis.

Figure 1.3 provides a basic example of using GIS to perform part of a risk assessment for three inventory items. First, the top box shows the spatial distribution of a hazard – in this case isopachs of tephra thickness. The middle box shows the three inventory items, which in this case are identical circles. The lower box shows the ability of GIS to combine the hazard map and the inventory map, to determine the hazard exposure of the inventory items, which is provided below the three boxes.

After the GIS is used to determine the hazard exposure, vulnerability information can be added in conjunction with attribute information to estimate risk to the inventory.

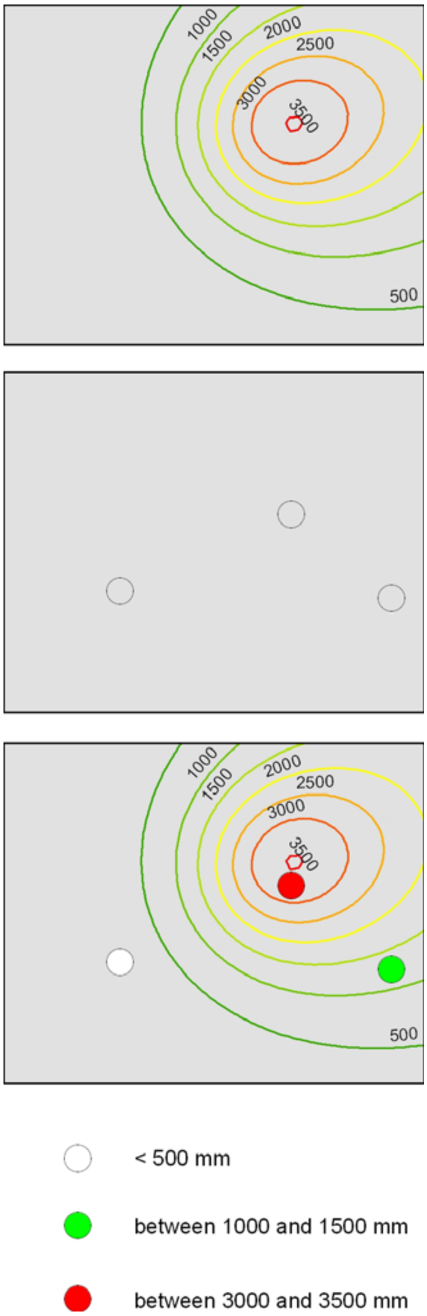

Figure 1.3 Example combination of hazard (top) and asset/inventory (middle) information in a GIS to provide hazard exposure (colours and text at bottom).

Risk would then be calculated if both:

a) information was available describing the attributes of the assets that make them vulnerable to the hazard (e.g. roof span length if they were buildings), and

b) fragility functions were available describing the expected damage ratios for the three inventory items at the given scenario tephra thicknesses (hazard intensity).

The asset on the left would have less risk to tephra, the asset on the right would have the next highest risk, and the top asset would have the greatest risk. RiskScape and RiskScape Volcano both make use of these basic GIS techniques to estimate risk on a scenario basis.

A useful example of GIS-based, non-probabilistic risk assessment that is comparable to that done in this thesis is that of Theirry et al. (2008) at Mount Cameroon in Africa. In that work, straightforward GIS techniques were used to combine inventory maps with simple hazards maps to determine risk to infrastructure around a volcano (Figure 1.4).

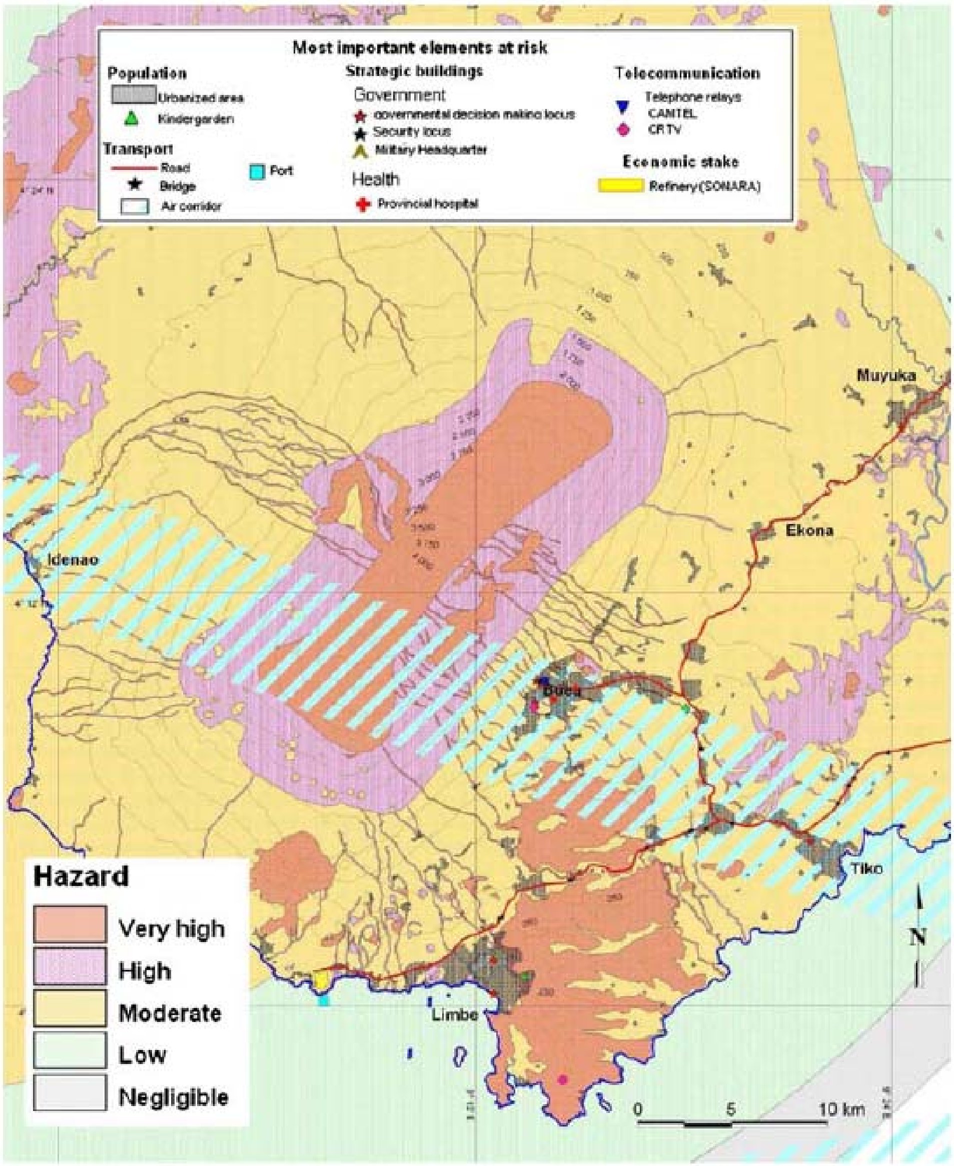

Figure 1.4 Hazard zoning (pastel colours) and infrastructure items at risk around Mount Cameroon as part of the GRINP project, from Theirry et al 2008.

The hazard zones are a simple factor of topography and slope; sophisticated computer models of volcanic hazards were not employed.

1.2.1.3 Computer Models as Volcanic Risk Assessment Methodology

Thousands of examples of scenario-based volcanic risk assessment methodologies exist, and many of the most recent studies rely on computational computer models for part of the volcanic risk assessment effort. Examples include Toyos et al.'s 2007 pyroclastic density current model used in this thesis, Sheridan et al.'s 2003 TITAN-2D model, Iverson et al.'s 1998 LAHARZ model, and many more. Each of these computer models is a risk assessment methodology. Because Publication IV provides a review of these and other volcanic hazard models and software, and Publications V and VI provide illustrative examples of the use of such programs, no further discussion is provided here.

1.2.2 Probabilistic Risk Assessment

1.2.2.1 Bayesian Event Trees

Neri et al. (2008 *in press*) provides an excellent example of recent probabilistic risk assessment for Vesuvius done as part of the EXPLORIS program that illustrates some of the state-of-the-art methodologies used in probabilistic volcanic risk assessment. One newly emerging probabilistic technique is that of a Bayesian Event Tree (Newhall and Hoblitt, 2002; Marzocchi et al., 2008). Bayesian Event Trees (BETs) provide a way of mapping out potential volcanic actions as compounded conditional probabilities, to illustrate the likelihood of occurrence of all possible types of events. A BET is summarized by Marzocchi et al. (2008) as:

1. A probabilistic model which merges all available volcanologic information (analytical and empirical models, historical data, monitoring observations) to derive the probability of any possible volcanic event
2. Provides the ability to falsify the results, or in other words test the plausibility of absolutely ANY hypothesis, no matter how unlikely
3. No events are ruled out, but the most likely events constitute a probability distribution based on the information gathered (item 1)
4. Both short and long-term eruption forecasting can be estimated, which can
    a. Allow comparative risk assessment
    b. Perform cost/benefit analysis of mitigation actions
    c. Demonstrate appropriate land use planning measures
    d. Put forward immediate risk –reduction actions such as evacuation

Figure 1.5 shows part of the BET for an explosive eruption at Vesuvius, from Neri et al. (2008 *in press*). Only the "explosive activity" branch is shown, as it is of more interest to risk assessment than the "non-explosive activity" branch. Under explosive activity, possibilities for eruptive category include Plinian, sub-Plinian I and II, violent Strombolian, continuous ash emission, and phreatic.

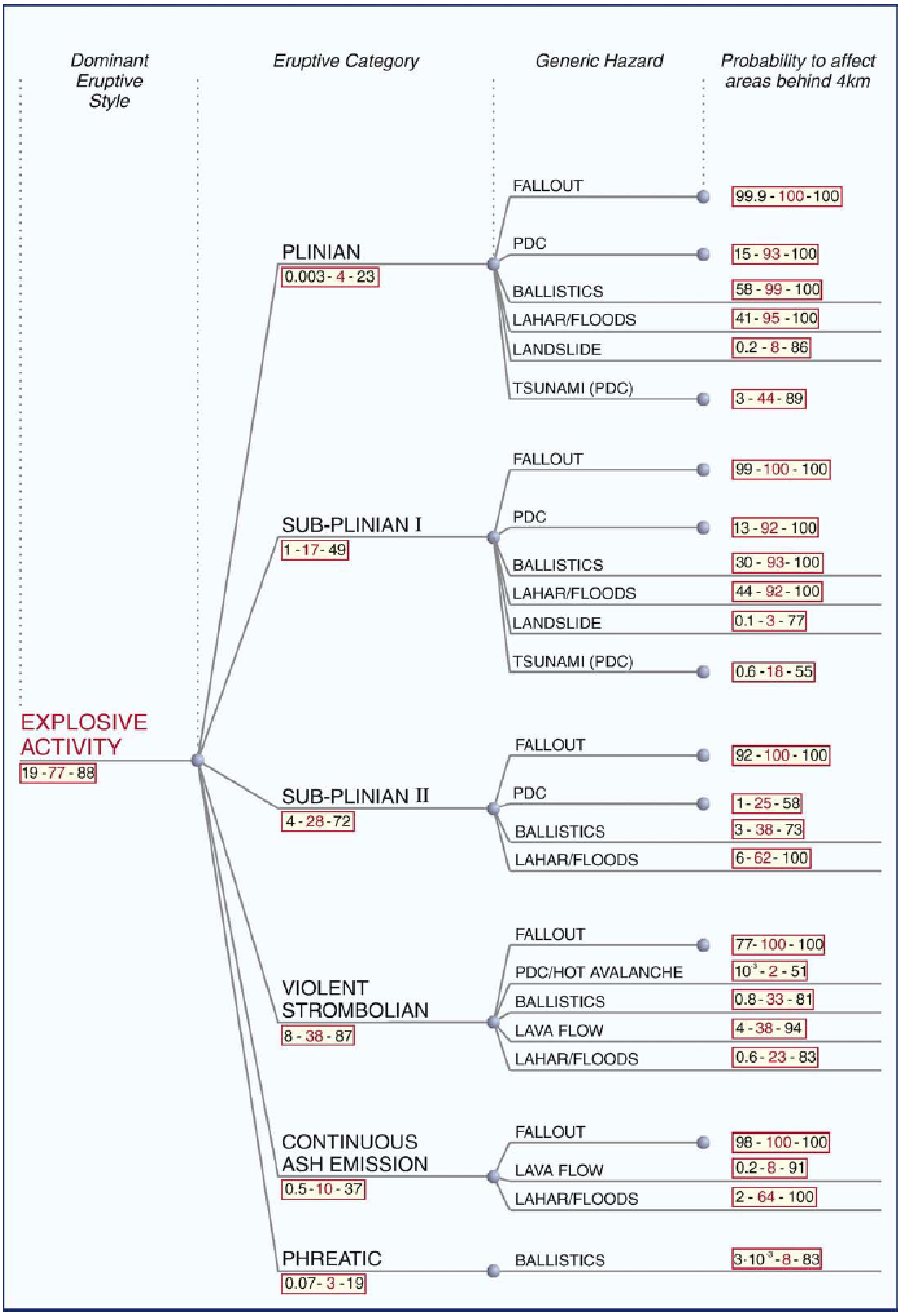

Figure 1.5 The explosive activity portion of the Vesuvius BET, with enumerated elicitation results from Neri et al. (2008).

Each category is shown along with its own 90% credible values (the modal or 50% value is in the centre, with the 5% value to the left and the 95% value to the right, giving the confidence limits of the probability). Then, moving to the right under each of those categories, potential generic hazards are shown. At the far right, the 5%-50% and 95% credible probabilities that each of the hazards will affect an area beyond 4 km from Vesuvius are shown. For example, the 50 percentile value that explosive activity in a violent Strombolian eruption will produce a lava flow that will impact areas more than 4 km from the volcano is 38%.

The conditional probabilities shown on a BET can then be used to determine the exceedance probabilities of events of different sizes (Figure 1.6).

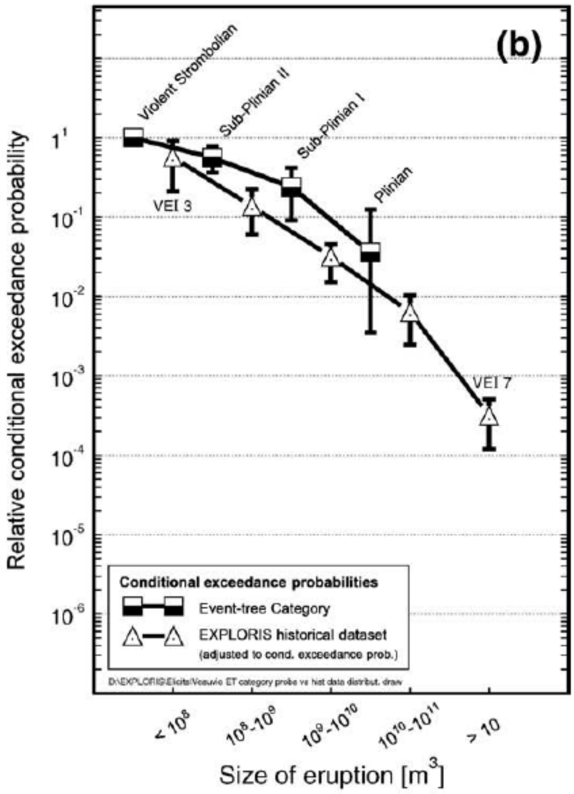

Figure 1.6 Comparison of probabilities from EXPLORIS' geological and monitoring dataset (triangles) and conditional exceedance probabilities (squares) for the different eruptive categories shown in the BET in Figure 1.4, from Neri et al., (2008).

This figure shows the relationship of the BET analysis with ordinary statistical analysis of data in EXPLORIS, and the two are in relatively good agreement.

Marzocci et al. (2008) authored a BET software program, BET_EF that allows users to create their own short and long term eruption forecasts based on the construction of BETs on user-supplied data. The software allows users to input information on monitoring thresholds and measures, as well as historical information about the volcano being studied. See Marzocchi et al. (2008) for more information and ways to obtain the software.

1.2.2.2 Monte Carlo Simulations

Monte Carlo simulations make use of repeated iterations of parameterized numerical models to achieve statistical understanding of different likely outcomes. In volcanic risk assessment, one example of applying Monte Carlo methodologies is a tephra dispersion model used to determine the relative probability of a certain ash thickness occurring at a given point within a certain annual exceedance interval. An example of such a study is the work of Bebbington et al. (2008, *in press*), in which the authors used Monte Carlo simulations to quantify the risks posed to electricity infrastructure at different locations around Mt. Taranaki (Figure 1.7).

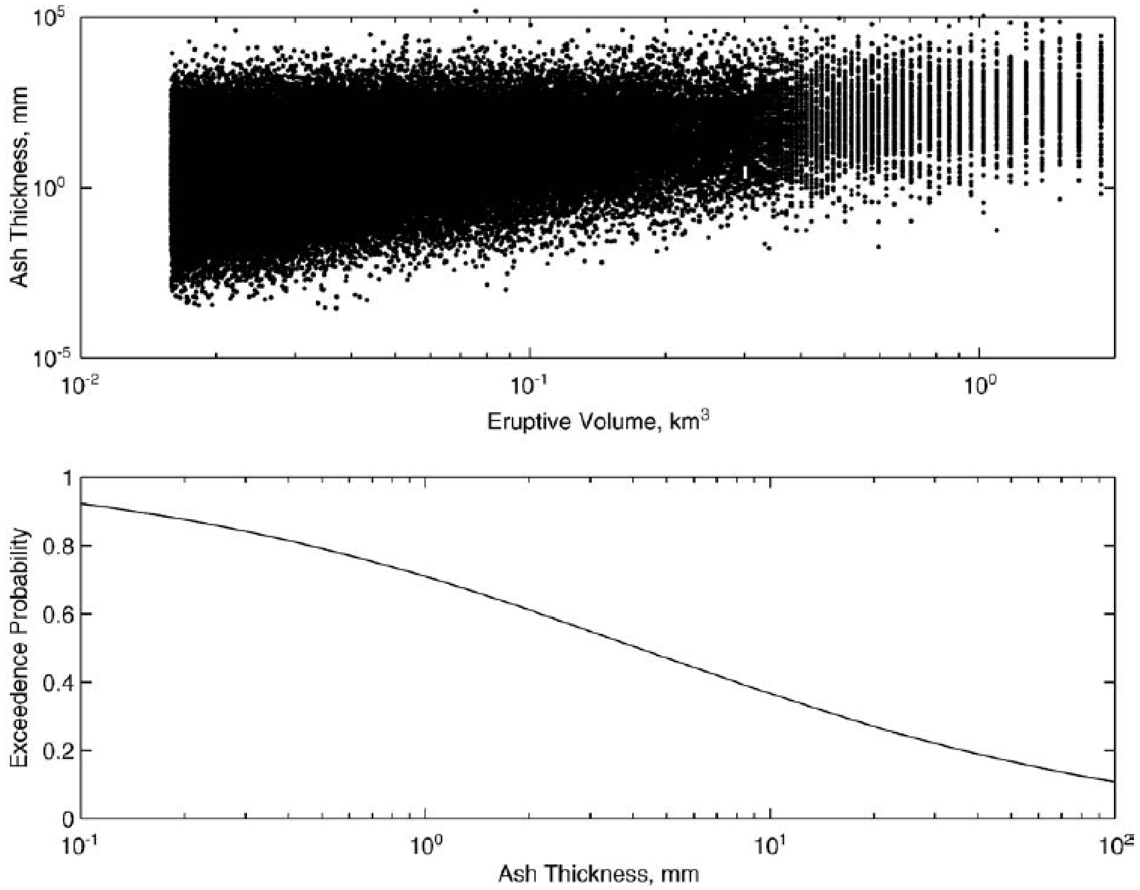

Figure 1.7 Tephra thickness at Stratford high-voltage electrical facility from the given eruptive volume (top), and the exceedance probability in a theoretical eruption, derived using Monte Carlo techniques, from Bebbington et al., 2008, *in press*.

The Monte Carlo technique has been widely used in volcanic risk assessment in New Zealand (e.g. Magill et al., 2005; Magill et al 2006b; Hurst and Smith, 2004; also see Table 1.3, below). Monte Carlo techniques are also widely used overseas. A recent example of Monte Carlo simulation used as a volcanic risk assessment methodology comes from the work of Zucarro et al. (2008 *in press*), which also stemmed form the EXPLORIS project. As one aspect of their methodology, the authors also used Monte Carlo simulations to derive collapse-load limits for buildings suffering from theoretical tephra loading, in order to develop fragility functions for the buildings in their overall risk assessment model.

There are numerous other examples of Monte Carlo methods used for probabilistic volcanic risk assessment, as the technique lends itself very well to understanding potential future volcanic activity.

1.2.2.3 Stochastic Forecasting

A stochastic volcanic risk assessment methodology is a non-deterministic method that applies the complicated mathematical technique of Kriging to time series of unrest data in order to forecast future volcanic activity (e.g. Jacquet et al., 2005; Jacquet and Carniel, 2003). Jaquet et al. (2005) provides an example of the application of such a technique via the DEVIN model used at the Soufriere Hills Volcano in Montserrat. DEVIN is a multivariate approach to eruption forecasting that enables:

1. detection and quantification of time correlation with variograms
2. identification of precursors by parameter monitoring
3. forecasting of specific events with Monte Carlo methods

Such methods are particularly useful in crafting forecasts at locations where volcano behavioural data is incomplete. A detailed review of stochastic forecasting methods is beyond the scope of this thesis; however they are worth noting because of their powerful ability to support eruption forecasting based on sparse time-series data of past eruptive activity.

1.3 Review of Volcanic Risk Assessment Efforts in New Zealand

This section provides a brief overview of relevant volcanic risk assessment efforts in New Zealand, to establish a context for discussing the development of RiskScape and RiskScape Volcano. New Zealand has many different active volcanic regions (Figure 1.8), all of which pose a variety of risk levels to the country based on location, eruptive character, potential eruption size and return period, and proximity to population, agriculture, and economic centres.

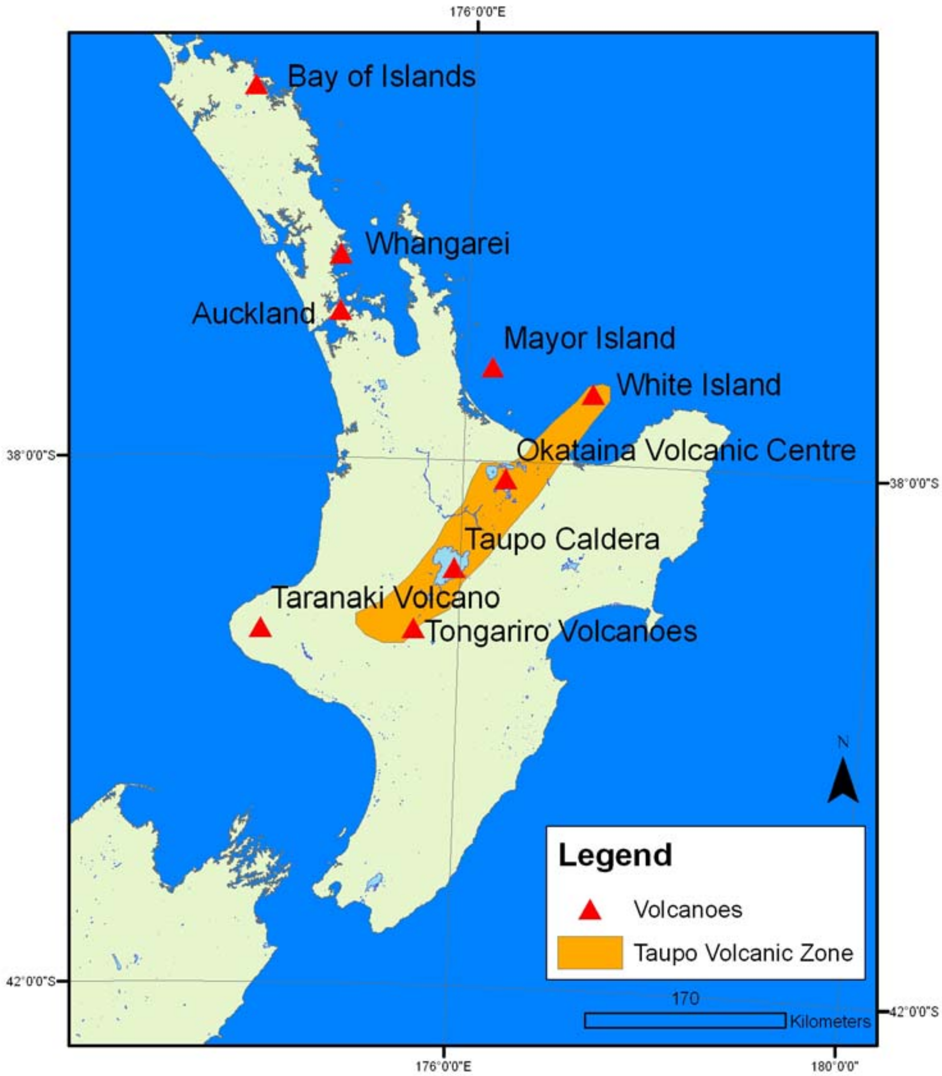

Figure 1.8 Volcanoes in New Zealand. Not shown are Raoul Island and the Kermadec volcanoes located off the figure to the northeast.

Table 1.2 summarises basic information about main New Zealand volcanoes, after Cousins et al., 2007a.

Volcanic Centre	**Most recent Eruption**	**Potential future eruption sizes (km^3)**	**Average return period**	**Key references**
Ruapehu	2007	Small (< 0.1) Medium (0.1 – 1.0) Large (>1)	20 100-500 10,000	Houghton et al., 1987; Neall et al., 1995
Ngauruhoe	1975	Small (<0.01) Medium (0.01 – 0.1)	10-20 100-200	Hackett and Houghton 1986
Tongariro	1896	Small (<0.01) Medium (0.01-0.1) Large (0.01-1)	100 1000 10,000	Hackett and Houghton, 1986
Taranaki / Mt. Egmont	1755	Small (0.01) Medium (0.01-0.1) Large (0.1)	300-500 1300-1600 10,000	Neall and Alloway, 1986
Taupo Volcanic Centre	181	Caldera unrest Small (<1) Medium (1-10) Large (>10)	10-20 1000-1600 2500-5000 5000-10,000	Wilson, 1993; Froggatt, 1997; Johnston et al., 2002c
Okataina Volcanic Centre (OVC)	1886	Caldera unrest Medium (1-5) Large (>5)	10-20 1500-2000 2000-5000	Johnston and Nairn, 1993; Scott and Nairn, 1998
Auckland Volcanic Field	~600 ybp	Small (<0.1) Large (1-2)	Poorly constrained	Magill et al., 2005; Allen and Smith, 1994

Table 1.2 Summary of volcanoes most likely to affect the central North Island, after Cousins et al., 2007a. Not shown are the Kermadec volcanoes, Whangarei, and the Bay of Islands due to the lower likelihood of having a significant impact on the North Island.

Considerable effort has been made to better understand the volcanic risks in New Zealand. Table 1.3 summarises work most relevant to this thesis.

Volcano	**Risk Assessment**	**Reference**	**Main points and/or limitations**	**Relevance**
OVC	Impacts of two different eruption scenarios to population and infrastructure in the Bay of Plenty.	Johnston and Nairn, 1993	Qualitative examination of impacts to people and infrastructure of the eruption of 1-2 km^3 of basaltic magma from the Okareka embayment, and the eruption of 8 km^3 of rhyolitic magma from Haroharo complex. Does not employ GIS to directly calculate risk, and is based on spatial distribution of hazards from prehistoric eruptions. Qualitative risk assessment.	Scenarios used in Chapter V were based on the scenarios in this paper. Provides first precursory model to RSV.
Ruapehu	Physical and social impacts of past and future volcanic eruptions in New Zealand, particularly the 1995/1996 eruption of Ruapehu	Johnston, 1997	Investigates the impacts of the 1995/1996 eruption of Ruapehu, also takes an in-depth look at the potential impacts of a future eruption on many physical infrastructure and social systems, also mentions caldera unrest (no eruption) as worthy of impact assessment.	Provides precursory vulnerability relationships for many infrastructure classes as well as scenario-based hazard model and ensuing risk assessment
AVF	Assessment of volcanic impacts for Auckland from an AVF eruption	Johnston et al., 1997	Considers hazards from five scenarios to investigate the risk to buildings, main infrastructure, critical facilities, population, economic activities, and natural features. Does not employ GIS. Qualitative risk assessment.	Precursor to RiskScape, but largely qualitative. Created foundation for subsequent AVF probabilistic modeling by Magill and Blong.
All NZ Centres	Investigation of the potential impacts of a volcanic eruption on agriculture and forestry in New Zealand	Neild et al., 1998	Detailed assessment of impacts of tephra fall on horticulture and forestry, using example of damage done and issues aroused by 1995/1996 Ruapehu eruption.	Proposes fragility functions for forestry and agriculture, based on Johnston, 1997 and expert input
OVC	Distal impacts if the ~1314 Kaharoa eruption were to be superimposed on modern New Zealand.	Johnston et al., 2000	Examination of impacts to infrastructure, agriculture, and socio-economic systems from tephra as a result of an eruption similar to the Kaharoa. Quantitative risk assessment.	Uses GIS to ascertain amount of population and different types of land cover within certain isopachs of tephra fall.
OVC	Proximal impacts if the AD 1314 Kaharoa eruption were to be superimposed on modern New Zealand	Johnston et al., 2002a	Model of damage to all aspects of society (mainly forestry and agriculture) from the Kaharoa eruptives within 10-20 km from Tarawera Volcano, and damage from post-eruption flooding along the Tarawera River.	Uses GIS to overlap Kaharoa deposits and different types of land area.

			Quantitative risk assessment.	
OVC	Impacts if the Whakatane eruption (~5500 y.b.p.) were to be superimposed on modern New Zealand	Johnston et al., 2004	Estimates of risk are given in terms of numbers of people impacted and damage ratios for trees, buildings, and forestry equipment. Cleanup costs are also considered, along with some agricultural impacts. Semi-quantitative risk assessment.	Uses GIS to overlap prehistoric hazard footprint (Whakatane eruption ash distribution) on modern society.
AVF	Probabilistic assessment of potential vent locations for the next Auckland eruption	Magill et al., 2005	Use of point-pattern and Monte Carlo techniques to determine probability of future eruption site. Authors suggest that as little as 18 separate events may have produced the 49 known features of the AVF. Probabilistic risk assessment.	Estimates risk by multiplying building density by vent density of simulated events based on locations of existing clusters.
All NZ centres	Volcanic risk ranking for Auckland (part 1 of 2), methodology and hazard investigation	Magill and Blong, 2005a	A ranking of possible risks to Auckland from eruptions at each of the North Island's main volcanic centres is given. Risk is defined as a product of likelihood, extent, and effect for each possible hazard from each volcano, which is then multiplied by the probability of a hazard occurring and the importance of the outcome. Taranaki is assigned the highest probability of eruption, with an AVF eruption having the highest risk for Auckland. Probabilistic risk assessment.	Ranks risk for Auckland; provides method for probabilistic consideration of hazard scenarios.
AVF	Volcanic risk ranking for Auckland (part 2 of 2) Examination of the consequences of the next Auckland eruption and calculation of risk	Magill and Blong, 2005b	Risk from tephra-caused building damage in Auckland is identified as the highest as a result of a Taranaki eruption. Risk to people from base surge (PDC) as a result of an on-land AVF eruption is the second highest. Sea-centred eruptions at AVF pose an order of magnitude less risk.	Compares one scenario to another, as does Chapter 13 (Publication IV)
Taranaki	Economic risk assessment of eruption from Taranaki / Mt. Egmont	Aldridge, 2006	Consideration of three small eruption scenarios' (two ash-producing and one unrest) impact on iconic (social as well as economic impact) industries.	Examines losses to infrastructure from different hazard scenarios as is done in Chapter s 12 and 13 (Publications V and VI)
All NZ centres	Probabilistic tephra fall simulation for Auckland	Magill et al., 2006a	Use of ASHFALL model to determine probability of different thicknesses of tephra	Uses ASHFALL model to determine probability of

			in Auckland from eruptions at major NZ volcanoes. Probabilistic risk assessment.	tephra thicknesses from different scenarios.
AVF	VolcaNZ volcanic loss model for Auckland	Magill et al., 2006b	Consideration of tephra fall hazards in Auckland from a Monte Carlo simulation of different eruption locations and sizes. Probabilistic loss model.	Provides loss model to buildings and
All NZ Centres	Assessment of volcanic and seismic risks to Taupo District Council assets.	Cousins et al., 2007a	Estimation of losses from volcanic hazards at different return periods. Semi-quantitative risk assessment.	Uses fragility functions and hazard scenarios to estimate risk and financial loss
OVC, TVZ	Assessment of seismic and volcanic risks to Carter Holt Harvey in and around Kinleith	Cousins et al., 2007b	Risk assessment for plant, and operation of Kinleith paper production facility from volcanic eruption and earthquakes. Uses probabilistic model to determine return periods for different sizes of eruptions, and gives damage ratios incurred by the hazards. Semi-Quantitative risk assessment.	Uses GIS to overlay geologic-record-based eruption scenarios onto modern society to estimate hazard exposure, and applies fragility functions to estimate risk.
All NZ Centres	Exposure of the dairy industry to volcanic hazards in New Zealand	Wilson, 2007	Uses seven scenarios from North Island volcanoes based on both historic and prehistoric eruption models as well as probabilistic tephra thickness models at different return periods, then applies fragility functions to estimate risk.	Uses fragility functions and eruption scenario hazard models in GIS s to estimate risk.
OVC	Investigation of effects of an eruption at the OVC to a dairy farm in Rotorua (Tulachard)	Wilson and Cole, 2007	Detailed examination of potential impacts of an eruption at the OVC on all aspects of one dairy farm near Lake Rerewhakaaitu in the Rotorua District	Examines damage to one farm in Rotorua via application of eruption scenarios, gives fragility estimations for dairying

Table 1.3 Summary of recent volcanic risk assessment efforts in New Zealand relevant to this thesis.

This table is an incomplete list of risk assessment efforts in New Zealand. For more information about these volcanic risk assessments, refer also to the citations in Table 1.2.

1.4 RiskScape

1.4.1 Importance of RiskScape

Prior to the initiation of the Regional RiskScape program (King and Bell, 2005) and engineering of the RiskScape software, a discrete standalone software tool for analyzing risk from natural hazards in New Zealand did not exist. RiskScape, when completed and delivered, will be the first such program, and will provide end users with the ability to determine exposure and risk from damaging hazard events. This is significant due to the combination of a high potential incidence of damaging natural hazard events in New Zealand and elevated levels of exposure to critical population centres, infrastructure, and valuable agricultural commodities. Many previous research efforts (e.g. Table 1.2, for volcanic hazards research) have been conducted to qualitatively identify exposure to such hazards, and the logical next step is to use advanced GIS techniques in a software package such as RiskScape to begin to quantitatively explore the exposures. This will provide support for decision-making in times of crises, as well as the development of strategies to mitigate and minimize loss from hazard events when they do occur.

1.4.2 Potential end users

Potential users of RiskScape include anyone who has a desire to better understand risks posed to New Zealand by natural disasters. Typically, this would be government organisations tasked with protecting and securing commerce, health and safety, or the economy. Examples include:

- Cabinet-level national government entities for all hazards, primarily:
    - The Ministry of Agriculture and Forestry
    - The Ministry of Civil Defence and Emergency Management
- District government organisations, such as:
    - The Rotorua District Council (e.g. risk from volcanoes)
- City governments, such as:
    - Auckland City Council (e.g. risk from volcanoes, tsunami)
    - Wellington City Council (e.g. risk from earthquakes, tsunami)
- Students performing academic risk reduction research at Universities
- Insurance analysts, seeking to determine insurance policies, regulations, and/or rates
- Overseas researchers hoping to develop a similar program elsewhere

1.4.3 RiskScape Main Steps

This section will briefly outline the RiskScape software, illustrating its design and utilisation via screen captures of an exemplary assessment of exposure of buildings in the Hawke's Bay to tephra fall from an eruption of Ruapehu volcano. The purpose here is not to fully illustrate the design or functionality of RiskScape; but to briefly detail the flow of the software to demonstrate the reasoning behind the design and structure of RiskScape Volcano, which will be discussed briefly in the next section and in detail in Chapter 11 (Publication IV).

RiskScape operates via six main steps:

1. Choice of hazard
2. Choice of hazard model
3. Definition of model parameters
4. Selection of assets (inventory) and level of aggregation
5. Selection of fragility function
6. Selection of fragility parameters

Figure 1.9 shows a screenshot of the RiskScape software, version 0.0.35 (December 2007). Each of the six main steps is selected along the left-hand side of the software. The middle window shows a map of New Zealand, with the model space outlined in yellow. The map can be panned or zoomed. The right window of the software provides the legend of displayed layers. The ability to change the order or symbology of layers does not yet exist in RiskScape. The absence of this basic GIS visualisation technique limits the model's ability to visualize hazard information, which will be discussed further in Chapter 5.

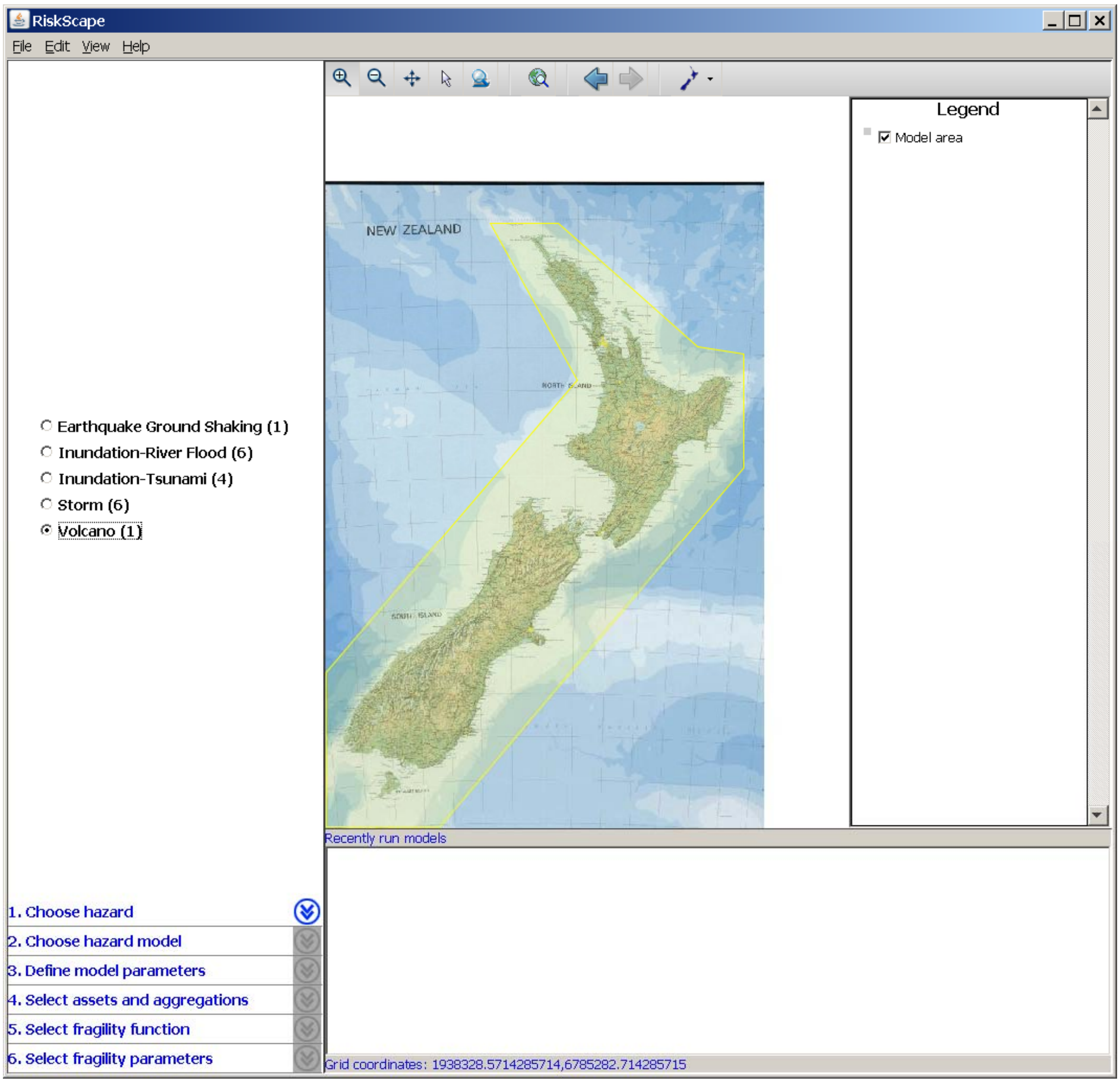

Figure 1.9 Screenshot of RiskScape software, showing the basic design and steps of model flow (left side).

Figure 1.10 shows the selection of the hazard model, in blue. At present, RiskScape only contains the ASHFALL model of Hurst (1994) for volcanic hazard risk assessment. RiskScape Volcano, once fully realised, will update RiskScape and add more choices to this step in the process, allowing the user to model risk to additional hazards with other models.

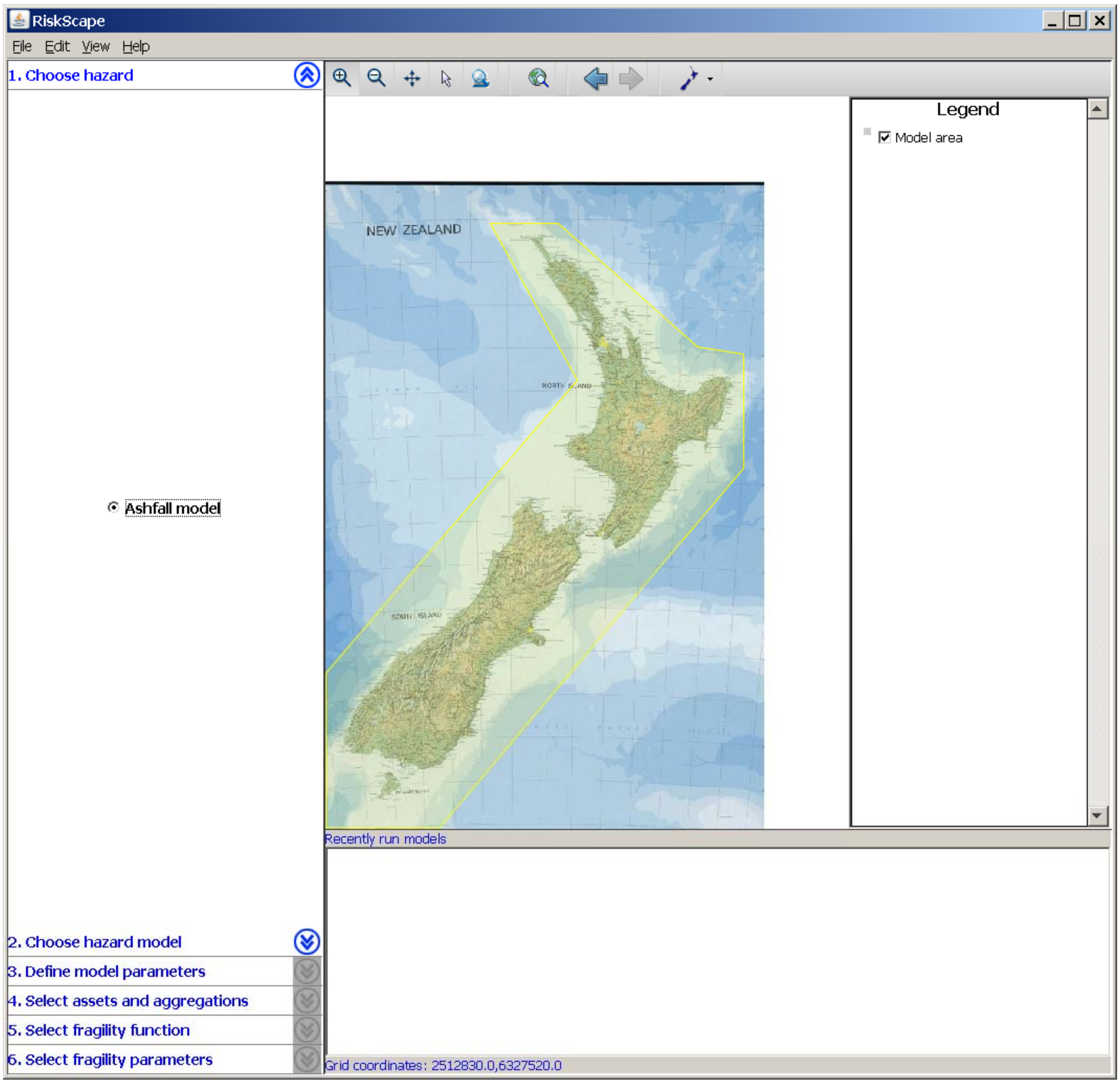

Figure 1.10 Selection of the hazard model.

Figure 1.11 shows the selection of the hazard model parameters. In this example run, the parameters relate to the ASHFALL model.

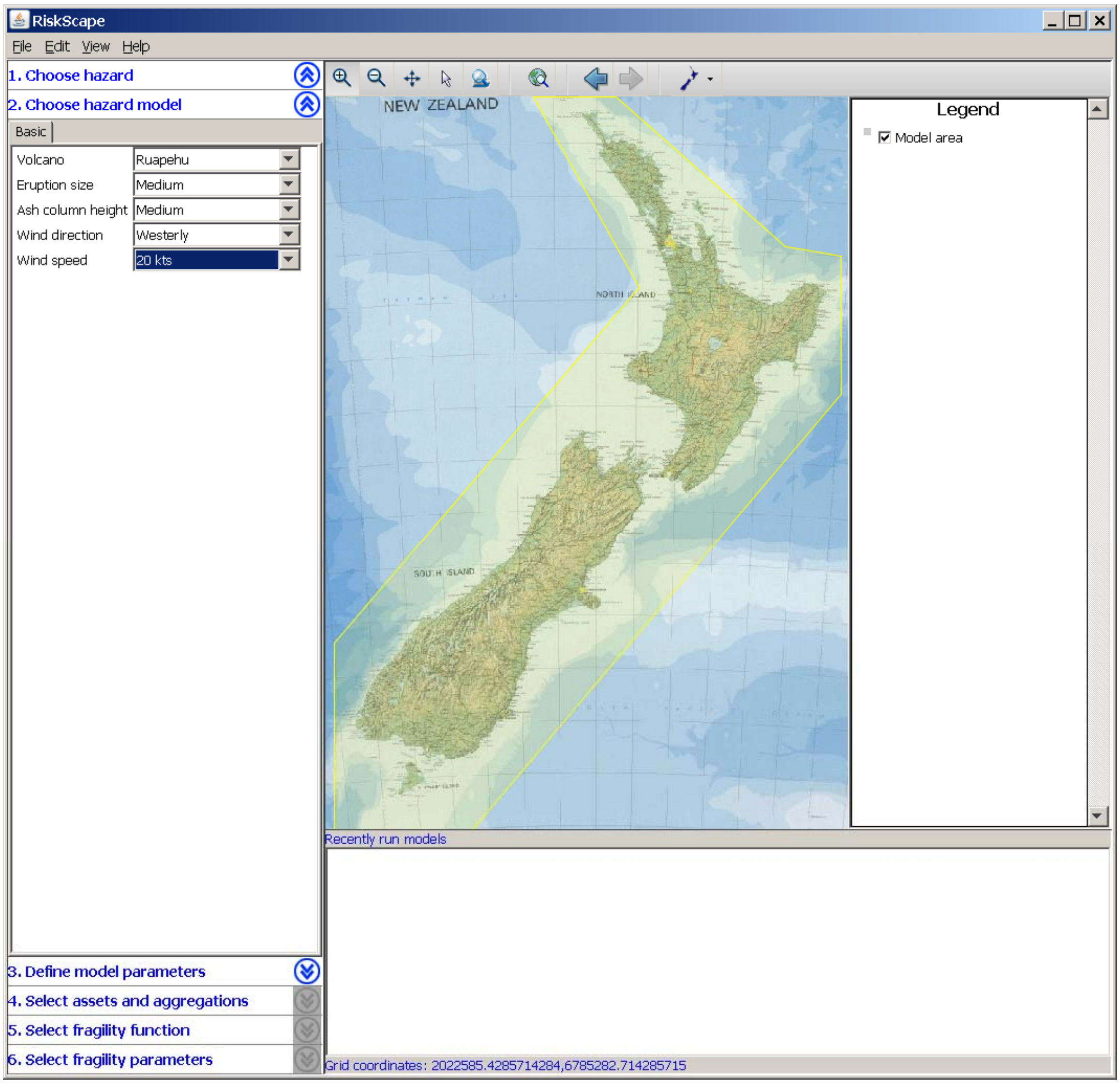

Figure 1.11 Selection of hazard model parameters.

Figure 1.12 then shows the output of the hazard model, or spatial distribution of hazard, which in this case is the thickness of tephra in mm (see legend in right column).

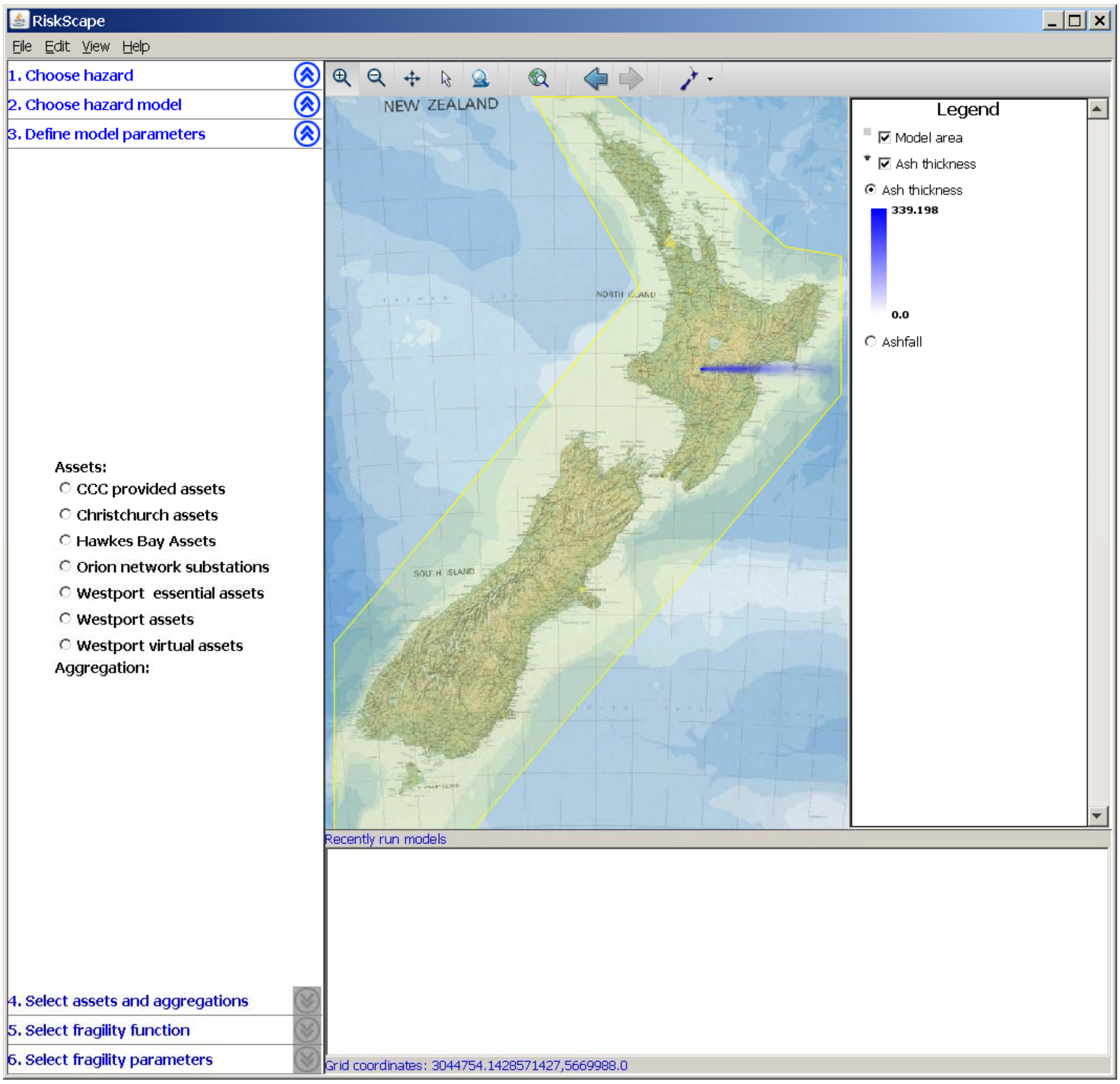

Figure 1.12 Hazard model output, showing ash thickness in shades of blue.

Figure 1.13 then shows the assets and aggregation level. At present, RiskScape aggregates assets at a meshblock level (meshblocks are units of population in New Zealand similar to census tracts in the United States). Assets are shown in the figure as green dots representative of a meshblock. Each displayed point is tied in the back-end of the software to a record in a text table which contains an aggregation of all of the appropriate asset information for assets within that meshblock.

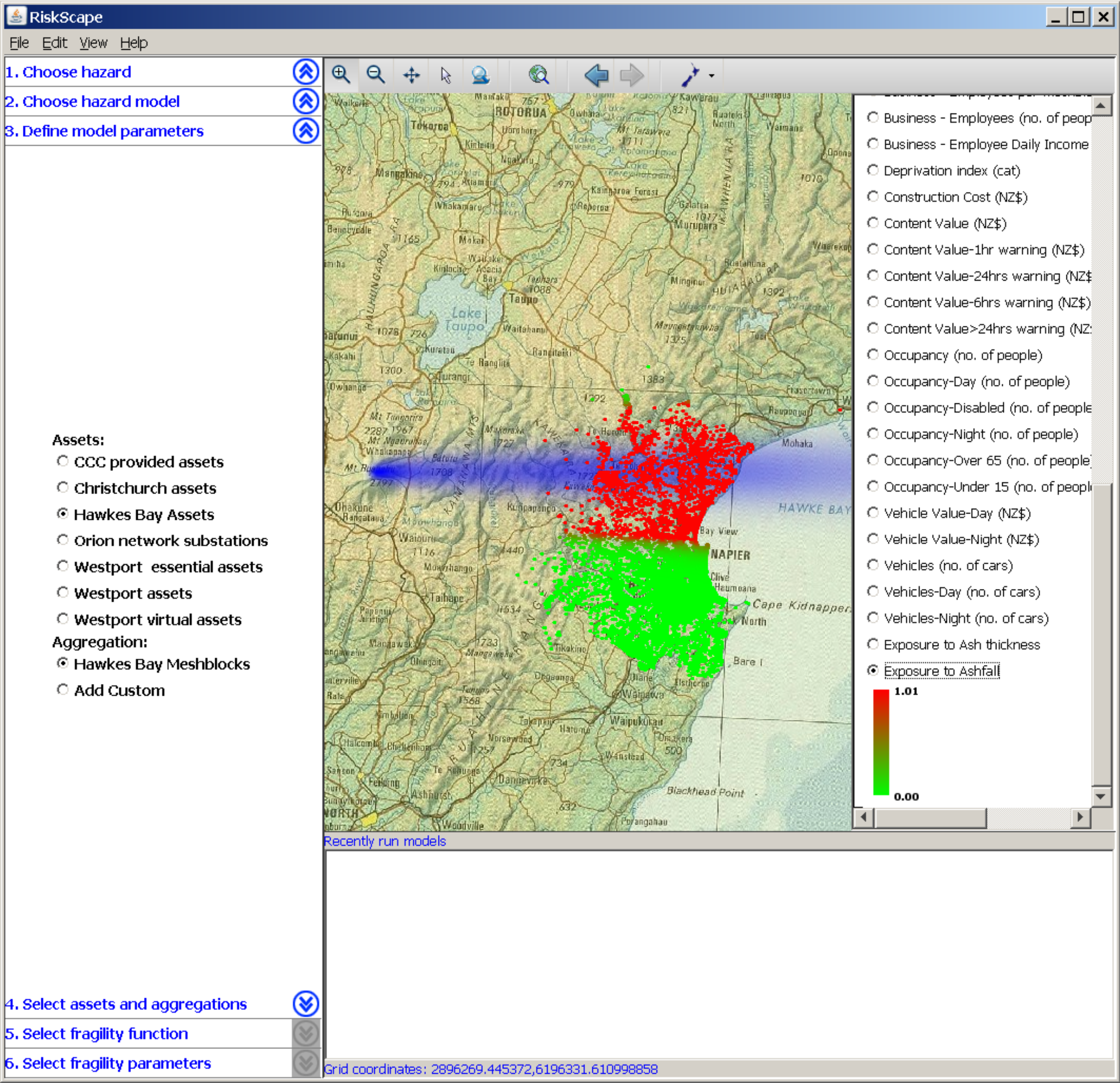

Figure 1.13 Assets, in this case exposure of meshblocks to ashfall (exposed = 1; red. Not exposed = 0, green).

Step 5, select fragility function, is not shown here because the latest version of RiskScape at the time of publication of this thesis did not yet have fragility functions loaded for tephra damage to buildings, vehicles, or population. These functions are given in Chapter 11 of this thesis (Publication IV), and will hopefully soon be incorporated in RiskScape.

1.5 RiskScape Volcano

The RiskScape Volcano model that has been created for eventual inclusion into RiskScape is discussed in Chapter 11 (Publication IV), and provides a detailed description of the design, components, and operation of the model, along with a theoretical example application. Chapters 12 and 13 (Publications V and VI) provide two instances of the model as it was tested and utilised in performing volcanic risk assessments. Refer to Chapter 11 (Publication IV) for more information about RiskScape Volcano.

1.5.1 Importance of RiskScape Volcano

RiskScape Volcano incorporates a select set of volcanic hazard models, fragility functions, and inventory databases into one model framework (Chapter 11). This methodology provides the RiskScape team with the means to add a full suite of volcanic hazards risk assessment capability to RiskScape, once key issues are resolved regarding the integration of RSV into RiskScape (discussed in Chapter 5.1). This work is important because of the high level of exposure of crucial New Zealand infrastructure, agriculture, and population to volcanic hazards such as an Auckland volcanic field eruption or a reawakened Mt. Taranaki. A heightened, quantitative understanding of the exposure of these entities throughout New Zealand to volcanic hazards is a vital part of bolstering the country’s future security in times of crisis.

1.6 Comparison to Similar Risk Assessment Efforts

Chapter 11 (Publication IV) contains a brief description of other efforts at volcanic hazard modeling with GIS or GIS-like technology: EXPLORIS in Europe and HAZUS in the USA. A more in-depth discussion of these efforts is provided here, with a focus on their strengths, weaknesses, and how RiskScape seeks to be different or improve the risk assessment process.

1.6.1 EXPLORIS

EXPLORIS is a collective effort between several universities and private research firms across Europe begun in 2002 to advance the understanding of risk posed to a selected set of European regions from explosive volcanic eruptions. The cities and volcanoes covered are given in Table 1.5.

Volcano	Region
Vesuvius	Naples, Italy
La Soufriere	Guadeloupe, France
Sete Cidades	Azores, Portugal
Teide	Canary Islands, Spain

Table 1.5 Volcanoes and regions covered by EXPLORIS

The goal of EXPLORIS is to exemplify means for providing decision-making support to governments both for planning before and during times of volcanic crises, based on the analysis of risk to people and infrastructure from explosive volcanic eruptions. This includes the objectives of developing a suite of eruption scenarios, deriving risk assessments from those scenarios, and investigating means of mitigating the risk. EXPLORIS can be divided into four main components:

1. Computer simulations to model explosive volcanic phenomena
2. Fragility functions and inventory databases
3. Protocols for probabilistic risk assessment.
4. Published papers providing results of application of the above three components to locations in Table 1.5

EXPLORIS focuses on human and building vulnerability to earthquakes, ash fall, and pyroclastic density current hazards.

EXPLORIS may become a paradigm shift in the field of volcanology (Baxter et al., 2008 *in press*), by ushering in a new era in which volcanic risk research is achieved via the application of probabilistic reasoning and statistical decision analysis. Its architects refer to this new approach as “evidence-based volcanology” (Baxter et al., 2008 *in press*). EXPLORIS and its research products heavily utilize the probabilistic risk assessment techniques discussed above in Section 1.2.2.

EXPLORIS is not discrete risk assessment software such as HAZUS or RiskScape, although collectively, aspects of the project comprise essentially the same functions as the inventory databases, hazard models, and vulnerability estimation functions as those found in RiskScape and HAZUS. The results of EXPLORIS include not only the software, computer simulation codes, vulnerability functions and methodologies developed to achieve the project’s goals, but also the risk assessments for the locations that were produced by those efforts (e.g. Baxter et al., 2008 *in press*; Neri et al., 2008 *in press*; Zucarro et al., 2008 *in press;* Macedonio et al., 2008 *in press*). The project also produced probabilistic BETs discussed in Section 1.2.2 above (Figure 1.5; further examples found in Marzocchi et al, 2008; Neri et al., 2008 *in press*) that are used to define the probability of different possible eruption scenarios. Some projects even involved analysis of seasonal wind statistics in Naples in the same manner as that done in Publication III in this thesis (Macedonio et al., 2008 *in press*).

Many of the papers cited in the publications that comprise this thesis were produced as a result of the EXPLORIS effort, including Macedonio et al., 2005; Spence et al. 2005a and 2005b; Gurioli et al., 2005 and 2006; Toyos et al., 2007; Neri et al., 2008 *in press*, Baxter et al., 2008 *in press*, Zucarro et al., 2008 *in press*, and Marzocchi et al, 2008. Furthermore, the Toyos et al. (2007) pyroclastic density current hazard model code (referred to herein as EXPLORIS-PDC) was used in this thesis to undertake the risk assessments in Publications V and VI, and is one of the hazard models cited in Publication IV.

1.6.1.1 EXPLORIS' Strengths and Weaknesses

As EXPLORIS is a collection of efforts and not a software package, it is difficult to compare directly to RiskScape. EXPLORIS' main strengths include the collective nature of the project, which allowed for a wide range of diverse groups' participation, as well as the application of risk assessment models to more than one geographic area. Because EXPLORIS is not a discrete software package like HAZUS or RiskScape, the discrete parts do not have to function together as a whole, nor does the development of the whole program have to be halted when single parts are upgraded or improved. EXPLORIS is also limited exclusively to assessment of risk from explosive volcanic eruptions, and does not contain any other types of hazard models. Some of the hazard models developed as part of EXPLORIS are technically complicated, and require application of parallel computing techniques (e.g. FALL3D and VOL-CALPPUFF). This can be limiting to users, should they desire to port these models to other volcanoes and apply them rapidly and with easily available computer hardware.

The end results of the EXPLORIS project consist mainly of published refereed journal articles that illustrate the application of various components of the project (e.g. Spence et al., 2005a and 2005b). The major results of EXPLORIS were beginning to appear in journal articles at the end of 2008, and there is no doubt that the program will have a profound impact on the "state of the art" of volcanic risk assessment, particularly with respect to the use of probabilistic techniques.

While these are useful in an academic sense as they illustrate the project's usefulness, until all of the models, vulnerability functions, inventory databases, and probabilistic scenario event trees are collected into one software package (if ever), EXPLORIS cannot be directly compared to RiskScape or HAZUS. In this way, EXPLORIS is more directly comparable to RiskScape Volcano (Publication IV) which is similarly a disparate set of hazard models, fragility functions, and inventory databases that can be combined with eruption scenarios to produce risk assessment results like those produced by EXPLORIS (e.g. Publications V and VI). EXPLORIS' products can be directly compared to the products of RiskScape Volcano (e.g. comparing Macedonio et al., 2008 *in press* to Publication VI).

1.6.1.3 How RiskScape Seeks to be Different than EXPLORIS or Improve Upon the Risk Assessment Process

RiskScape seeks to differ from EXPLORIS and improve the risk assessment process by collecting its own equivalent components in one software environment, allowing users control over which hazards are modelled, which parameters are used to model them, which inventory datasets and vulnerability functions are used, and which risks are assessed. RiskScape also seeks to only involve software models within itself that can function on widely available computers and operating systems (i.e. no parallel computers or UNIX-based routines). RiskScape also differs from EXPLORIS in that it does not attempt to explicitly address issues of probabilistic risk assessment. When RiskScape Volcano is incorporated into RiskScape, the resultant software package will be much more like HAZUS than EXPLORIS. RiskScape also seeks to improve on the risk assessment capabilities of EXPLORIS by incorporating more than one natural hazard type.

1.6.2 HAZUS

HAZUS is a multi-hazard risk assessment software tool authored by the US Federal Emergency Management Agency (FEMA). HAZUS permits federal, state, regional, and local governments to better plan for and mitigate against losses from earthquakes, floods, and hurricanes. HAZUS operates on the Windows XP platform (although only with SP2), directly through ESRI's ArcGIS software. HAZUS comes with a single-use copy of ArcGIS and the Spatial Analyst extension, both of which have been specially modified and can only be used with the HAZUS application. Because HAZUS operates via ArcGIS, users can easily incorporate their own ancillary user-supplied datasets, such as shapefiles of local political boundaries, satellite imagery, et cetera.

Users of HAZUS can only work on one hazard at a time. HAZUS has five main steps:

1. Identify hazards
2. Profile hazards
3. Inventory assets
4. Estimate losses
5. Evaluate mitigation options

Users navigate through HAZUS by first defining a region for analysis, and then choosing an aggregation level for that analysis. These steps are similar to those used in RiskScape (section 1.43, above), with the notable exception of HAZUS' step 5. RiskScape does not make any attempt to address mitigation within its software environment; such exercise is left to the user to pursue on their own outside of the software, utilizing its results.

1.6.2.2 HAZUS' Hazard Models, Inventory Datasets, and Fragility Functions

HAZUS has three main hazard models: an earthquake model, a flood model, and a hurricane wind model. Refer to the technical manuals published by FEMA, available online at the following URL (http://www.fema.gov/plan/prevent/hazus/hz_manuals.shtm) for more detailed information. The hazard models are the result of nearly 20 years of multi-disciplinary effort by hundreds of researchers in universities and colleges, government agencies, the military, and the private sector. They include both work done specifically for HAZUS and research resulting from collaboration with overseas researchers in the respective hazard fields.

The HAZUS models differ from the hazard models referred to in Publication IV of this thesis (RiskScape and RiskScape Volcano hazard models) in that the HAZUS models are more all-inclusive of the overall risk assessment methodology as they contain physical numerical routines for mapping hazard conditions, as well as inventory datasets, and vulnerability estimation functions. "Hazard models" in RiskScape and RiskScape Volcano refer specifically and exclusively to numeric models that output the spatial extent of hazard conditions (e.g. ASHFALL). Hazard models in HAZUS include inventory and vulnerability estimation methods (fragility functions).

After the user chooses the region in which they wish to undertake the risk assessment in, they choose the hazard, and then the inventory they wish to include in the risk assessment. HAZUS users can choose three aggregation levels of inventory data and thus loss estimation – state, county, or census tract. In New Zealand, this would roughly correlate to region, district, and meshblock. HAZUS ships with the following national inventory datasets, for the entire USA:

- Political boundaries (state, county, and census tract boundaries)
- Aggregated building information (square footage, building counts by occupancy)
- Essential facilities (police, fire, schools, hospitals, emergency operations)
- High potential loss facilities (dams, nuclear power plants)
- Transportation systems (highways, railways, bus stations, ports, harbours, ferries, airports)
- Lifeline utility systems (potable water, wastewater, oil, electric, power, communication systems)
- Hazardous materials
- Agricultural products (crops by type, average yield, unit, and harvest price)
- Demographic data (housing and population statistics, income, occupancies, housing units all from 2000 US Census).

Like RiskScape, HAZUS makes use of fragility functions that are integrated into the risk assessment methodology. These functions have the same shape and purpose as the functions used by RiskScape, in that they directly relate expected damage ratio to a physical hazard characteristic (e.g. Figure 1.14, relating D_r to earthquake spectral displacement).

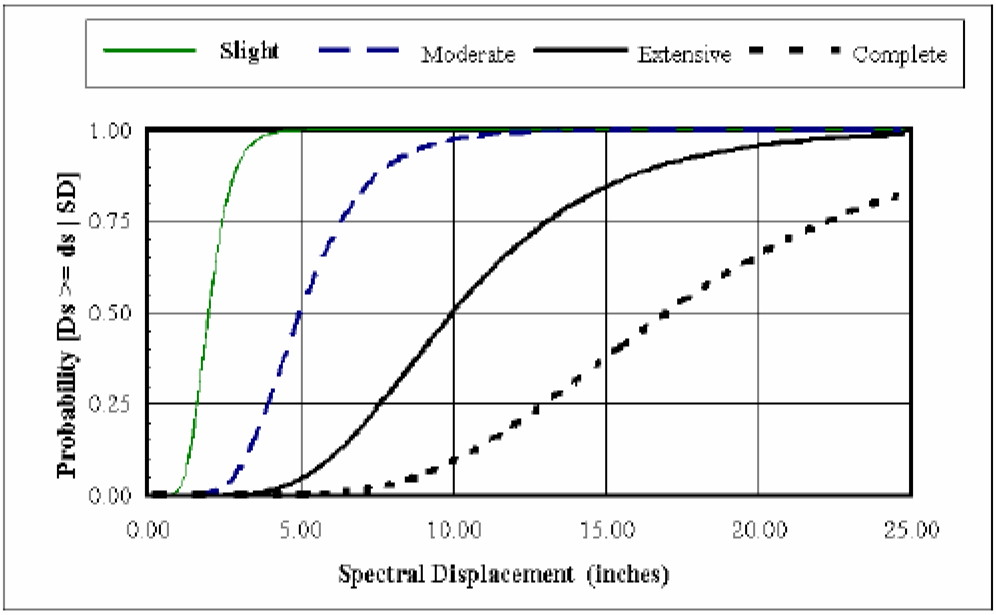

Figure 1.14 Fragility functions from HAZUS earthquake model for slight moderate, extensive, and complete damage to buildings, from FEMA, 2003.

1.6.2.3 HAZUS' Strengths and Weaknesses

HAZUS has many strengths. Its foremost strength is the successful combination of its powerful, complex hazard assessment engines and strong scientific underpinning and ease of use, mainly due to its operation via the ArcGIS software on the Windows platform. This allows users familiar with ArcGIS to easily adapt to HAZUS workflow. Users can also quickly and easily incorporate existing GIS data (e.g. boundaries, etc.) with HAZUS components to aid in communicating risk assessment results. Common GIS tasks such as projecting data from one map projection to another, or creating subsets of data are easily and quickly performed within ArcGIS. RiskScape does not yet have this functionality; more on this issue will be presented in Chapter 5.1 of this thesis. This can also be a weakness for HAZUS if end users are not experienced with ArcGIS. The fact that HAZUS ships with a functioning demo version of ArcGIS helps users become familiar with the software quickly and at cost.

The inventory datasets that ship with HAZUS are extensive and contain a plethora of information that is needed to conduct risk assessments over moderate to large-sized regions. The HAZUS default datasets are a substantial strength of HAZUS in that the software ships ready-to-use with voluminous inventory data for a wide variety of inventory classes, including critical infrastructure, population, and agriculture. FEMA also makes a tool for collecting HAZUS-compatible inventory datasets, called inCAST, which allows users to create their own inventory datasets. One weakness of the HAZUS system is that users can actually use the software to examine losses at an individual building level; however this is not appropriate as the results are actually an average across all buildings of that type at the census tract aggregation level. Furthermore, the HAZUS earthquake model explicitly states that at best, its loss estimates have a range of uncertainty of a factor of two or more.

The three hazards currently included in HAZUS are the three main hazards capable of causing the most extensive damage to populations in the USA, and thus the choice of the hazards can be considered to be one of the program's strengths. The obvious lack of any volcanic hazard risk assessment in HAZUS, however, is a glaring weakness. Although the United States does not have as extremely elevated a level of volcanic hazard as New Zealand, nevertheless there are potentially dangerous volcanoes there that lie within harms way of cities, important infrastructure and agriculture. Mt. Rainier and Mt. Hood are examples of very dangerous volcanoes that would pose enormous risk to the US in the event of large eruptions at either volcano. Future versions of HAZUS should include the capability of examining risks from the major volcanic hazards, such as tephra dispersion and pyroclastic density currents.

1.6.2.5 How RiskScape Seeks to be Different than HAZUS or Improve the Risk Assessment Process

RiskScape is largely an effort to create a HAZUS-like software package that achieves the same goals for New Zealand that HAZUS has for the USA: delivery of a multi-hazard loss estimation software tool capable of enabling natural hazard loss estimation for all levels of government. This would support emergency and land-use planning, as well as decision making in times of crisis, and therefore mitigate losses from natural hazard events. As a point of fact, RiskScape was originally conceived with HAZUS in mind as template software in terms of basic functionality (A. King, GNS Science, *pers. comm.*, 2005). As it develops, RiskScape will eventually improve upon HAZUS, in that it will be tailored more specifically to New Zealand hazards and inventory stocks, and therefore become more effective than simply adapting the HAZUS software to work in New Zealand.

The main area in which RiskScape seeks to differ from HAZUS is the choice of its developers to not make use of ArcGIS. The wisdom of this decision remains to be seen, and will be discussed with regards to RiskScape Volcano in Chapter 5 of this thesis. As of the end of 2007, RiskScape has yet to achieve the same levels of functionality and usefulness as HAZUS, although its development has been undertaken in a much shorter timeframe and with less funding and support. RiskScape will undoubtedly improve the risk assessment process as the software develops, and builds upon the methodologies found in HAZUS, EXPLORIS, and in other risk assessment efforts undertaken beyond the shores of New Zealand.

2. GOALS AND RESEARCH QUESTIONS OF THIS THESIS

This section outlines the goals of this thesis, and also presents the research questions it intends to answer via each of its separate publications, and together as a complete body of work.

2.1 Goals

The thesis (publications and the thesis itself) has the following goals:

1. Take field observations of volcanic impacts (Chapter 8 / Publication I) and use them as a basis on which to construct agricultural fragility estimation functions for New Zealand agriculture (Chapter 9 / Publication II) that can be applied in a risk assessment to agriculture in the Rotorua District (Chapter 12 / Publication V) via a risk assessment model (Chapter 11 / Publication IV).
2. To create a heightened understanding of the wind patterns above the central North Island of New Zealand (Chapter 10 / Publication III), that can be used to facilitate realistic modeling of tephra dispersal in a risk assessment in New Zealand (Chapter 12 / Publication V).
3. To create a new model for estimating risk from a full suite of volcanic hazards, “RiskScape Volcano” (Chapter 11 / Publication IV) that expands the scope of the RiskScape software, along with an outline of issues involved with integrating the model into RiskScape (Chapter 5)
4. To test that model via assessment of risk from selected volcanic hazards to selected inventory items in Rotorua, New Zealand (Chapter 12 / Publication V) and Mammoth Lakes, California, USA (Chapter 13 / Publication VI) based on the model design and procedures outlined in Chapter 11 / Publication IV.
5. To measure the level of volcanic hazards awareness in the tourism sector in Mammoth Lakes (Chapter 14 / Publication VII), which provides a basis for subsequent measurements after publication of risk assessments (e.g. Chapter 13 / Publication VI).
6. All of the above goals fall under the overarching goal of this thesis – to create and test a volcanic risk assessment model for the RiskScape program that advances the field of volcanic risk assessment.

2.2 Research Questions

The goals proposed in Section 2.1 will be met via answering the following research questions:

1. What were the impacts to agriculture and infrastructure during the 2006 eruption of Merapi Volcano in Indonesia? How are these impacts relevant to agriculture and infrastructure in New Zealand (Chapter 8 / Publication I)?
2. How is agriculture in New Zealand impacted by tephra accumulation (Chapter 9 / Publication II)?
3. What patterns, if any, exist in wind above the central North Island, and how can a heightened understanding of these patterns be used to improve modeling of tephra dispersal with ASHFALL model (Chapter 10 / Publication III)?.
4. How should an effective, useful GIS-based volcanic risk assessment model for RiskScape (RiskScape Volcano) be constructed (Chapter 11 / Publication IV)?
    a. What are the best volcanic hazards models for RiskScape to use?
    b. What is the best level of inventory data for an effective first-order hazards assessment in a large community?
    c. What aspects of a society are critical? What infrastructure does this include?
    d. What are the vulnerabilities of different types of inventory?
    e. What scales of potential future eruptive activity should be considered when constructing an eruption scenario for risk assessment?
5. What impact would a rhyolitic eruption from the Haroharo Volcanic Complex at the Okataina Volcanic Centre have on people, agriculture, and infrastructure in Rotorua (Chapter 12 / Publication V)?
6. What would be more damaging to critical infrastructure in Mammoth Lakes, California in the USA, a Mammoth Mountain eruption or an Inyo Domes eruption (Chapter 13 / Publication VI)?
7. What is the level of volcanic hazard awareness in the tourism sector in Mammoth Lakes, California (Chapter 14 /Publication VII)?
8. Should RiskScape's volcanic risk assessment model follow the model / normal design of RiskScape?
9. What is a good model workflow and menu design for RiskScape Volcano in RiskScape?
10. What are the main issues involved with integrating RiskScape Volcano into RiskScape?
11. How does RiskScape Volcano advance the field of volcanic risk assessment?

3. GEOLOGIC BACKGROUND OF ROTORUA DISTRICT AND THE OKATAINA VOLCANIC CENTRE

This chapter provides a detailed geologic background for the region that is the subject of Chapter 12 (Publication V). Rotorua District (Figure 3.1) lies to the west of the Okataina Volcanic Centre (OVC; Figure 3.2) in the Taupo Volcanic Zone (TVZ) in the Bay of Plenty region of New Zealand's North Island.

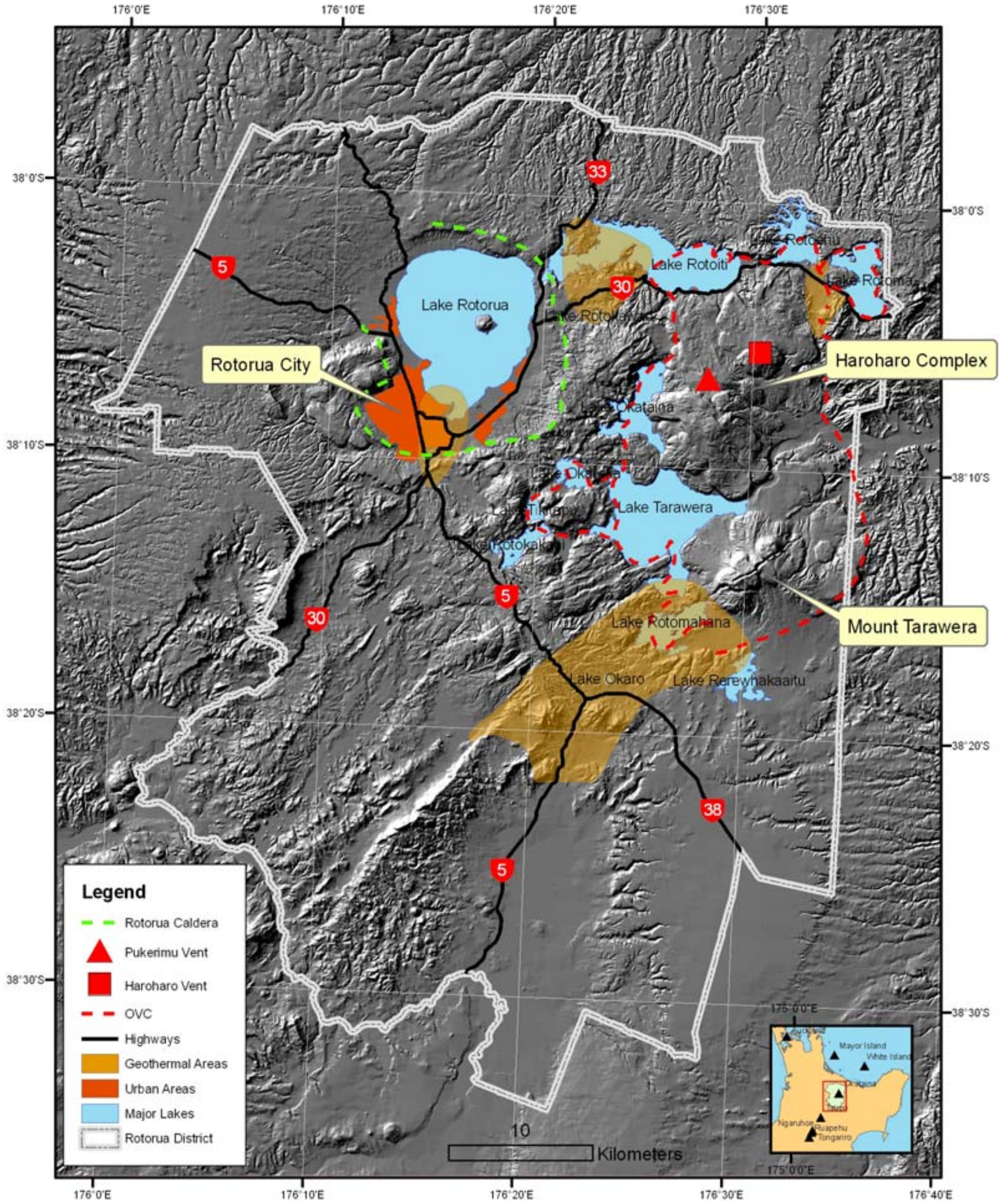

Figure 3.1 Shaded relief map of the Rotorua District, showing the outline of the Okataina Volcanic Centre, (broken red line), Rotorua Caldera (broken green line), and geothermal areas in the district (orange shading – all after Nairn, 2002 and Scott and Nairn, 1998).

The OVC is the north-eastern most large rhyolite caldera in the TVZ. Nairn (2002) provides an excellent and thorough discussion of the geology, hazards, and history of the OVC, and the reader is referred to that work if a detailed treatment of its history is required. In this chapter, the focus will be on aspects of the history of the OVC relevant to potential future volcanic hazards in the Rotorua District. Attention will be focused on the young (<22 ka) eruptive episodes at the OVC, as well as to a few significant older eruptions. Reviews of the literature provide a description of the deposits left by these eruptions, along with interpretations of the processes that created them.

3.1 Regional and tectonic setting – the Taupo Volcanic Zone (TVZ)

In the greater context of the regional geologic setting of the central North Island, the TVZ (Figure 3.2) is the active volcanic back-arc basin of the Taupo-Hikurangi arc-trench system (Cole, 1990). Subduction along this trench occurs at the rate of ~7 mm / year (Villamor and Berryman, 2001), and is not orthogonal (Cole and Lewis 1981). A high heat flow exists in the TVZ, on the order of 4,200 MW through a thin ~30 km crust (Henrys et al., 2003). The TVZ is widely considered to be the most productive volcanic system on earth, producing 0.28 m^3/sec of rhyolitic magma for at least the last 0.34 Ma (Wilson et al., 1995).

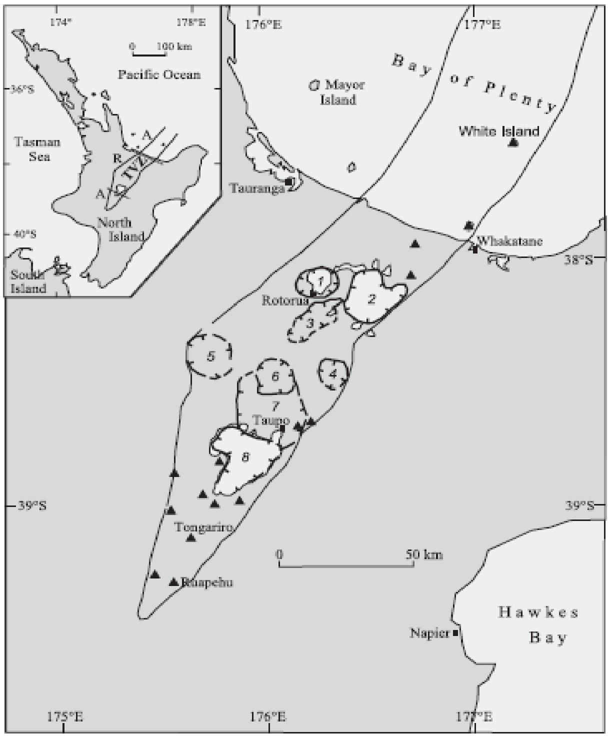

Figure 3.2 The Taupo Volcanic Zone (after Cole et al., 2005b). The Okataina Volcanic Centre (OVC) is shown as #2.

Two of the largest known eruptions in the last 50 k.y. have emanated from the TVZ, the ~530 km^3 magmatic equivalent Oruanui eruption at 26.5 ka (Wilson, 2001), and the 233 A.D. Taupo pumice eruption (Lowe et al., 2008) that released 60-100 km^3 of tephra from present-day Lake Taupo (Wilson et al., 1995). Overall, Wilson et al. (1995) estimate the total volume of material erupted from the TVZ as between 15-20,000 km^3. More recently in the last 22 ka in the OVC, there have been eleven major rhyolitic eruptive episodes, producing almost 85 km^3 of magmatic equivalent (Table 3.1, Nairn, 2002).

The TVZ can be subdivided into three zones – the southwestern Tongariro segment (andesite-dominated), the central Taupo/Okataina segment (rhyolitic), and the northeastern Bay of Plenty Segment (andesite-dominated), shown in the inset of Figure 3.2 (Cole et al., 2005b). Within the OVC, rhyolitic volcanism cannot be found northeast of Kawerau (upper right, Figure 3.3; Cole et al., 2005b; Cole, 1990).

Figure 3.3 shows the main large rhyolite calderas of the TVZ. Shaded areas depict exposed Mesozoic greywacke basement rocks, while unshaded areas are TVZ ignimbrites, young OVC lavas and eruptive products, and quaternary fluvial deposits (after Nairn, 2002).

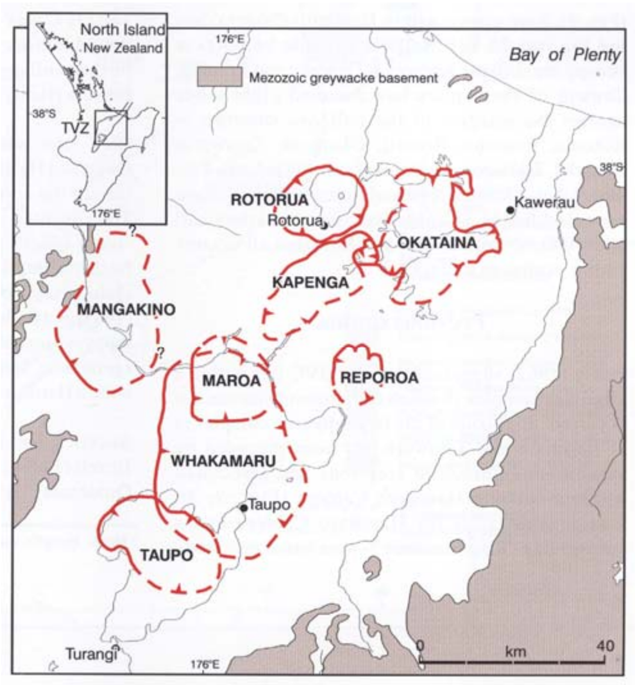

Figure 3.3 Schematic map of calderas and intracaldera dome complexes (Maraoa) of the TVZ, from Nairn (2002). Okataina (far right-top) and Rotorua (top centre) are the northeastern-most and northwestern-most TVZ calderas (respectively).

Figure 3.4 provides an overview of the morphology of the OVC region in a shaded relief map. While the Rotorua Caldera is not physically within the conventional boundaries of the OVC (as per Figure 3.3), here its history is discussed along with that of the OVC because of its relevance to hazards in Rotorua City. It is worth noting, however, that the Rotorua Caldera is no longer "active" per se (save for its active hydrothermal systems), and today only the Taupo and Okataina volcanic centres can be considered "active" (Smith et al., 2006).

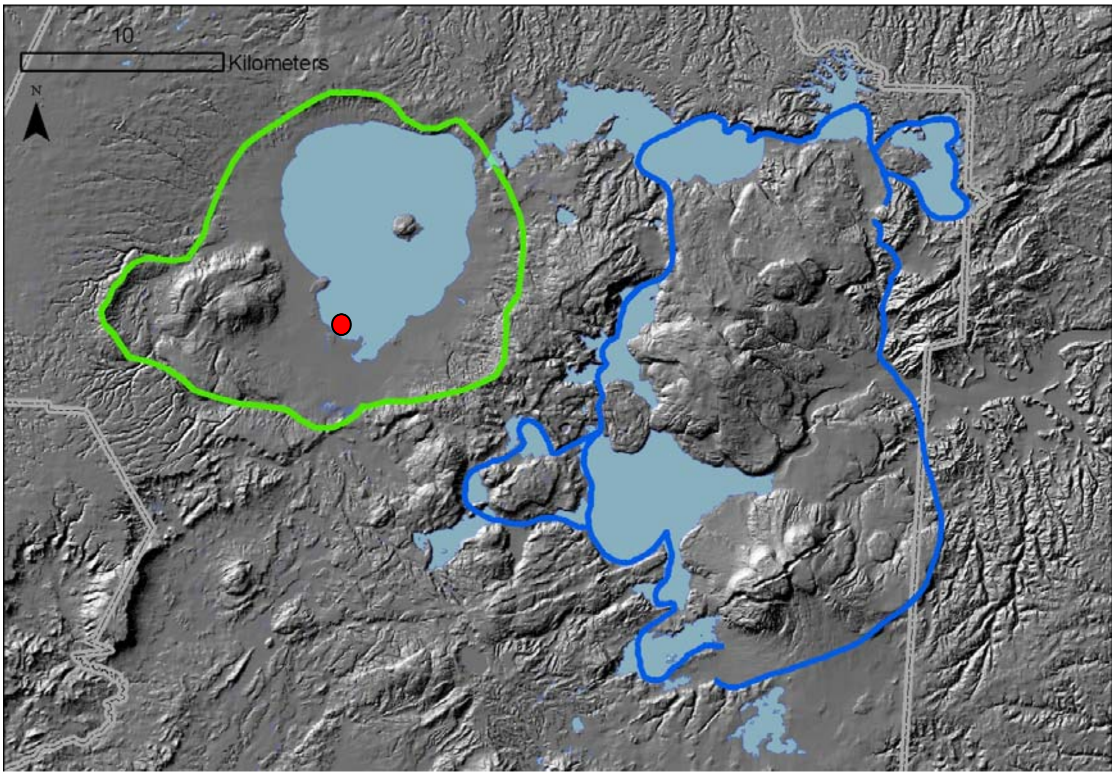

Figure 3.4 Physiography of the central Rotorua District, showing the approximate structural outlines of the Rotorua Caldera (green) and the OVC calderas (blue), both after Nairn, 2002. Rotorua city is shown as a red dot.

3.2 The Okataina Volcanic Centre - Geologic Background

Here, significant eruptive episodes at the Okataina Volcanic Centre are discussed. For each eruption or eruptive episode, the following characteristics will be highlighted (as inferred via field investigations in the literature, wherever possible):

- Age of eruption
- Deposits – location, extent (km^2)
- Physical processes – lava flows, pyroclastic flows, dome emplacement etc.
- Duration and timing (onset to conclusion)
- Height of largest eruption column
- Amount of magma erupted (km^3)
- Amount of D.R.E material erupted (km^3)

3.2.1 Eruptive History of the OVC

Prior to the arrival of people to New Zealand, volcanic activity at the OVC was prolific, producing numerous large eruptions. Table 3.1 gives the ages and volumes of the major intra-caldera OVC eruptive episodes less than 22 ka in age (after Nairn, 2002).

The geologic background / history of selected eruptive episodes from Table 3.1 will be given here, with emphasis on the two episodes that have been chosen to serve as examples for future hazard risk assessment in Chapter 6: the Tarawera 1886 eruption, and the Kaharoa A.D. 1314 eruption.

Eruptive Episode	**Age (ka)**	**Lava volume (km^3)**	**Pyroclastics volume (km^3)**	**Equivalent magma volume (D.R.E.; km^3)**	
				Haroharo	***Tarawera***
Tarawera Basalt	(1886 A.D.)	-	2[1]	-	0.7
Kaharoa	0.7	2.5	5	-	5
Rotokawau Basalt[2]	3.4	-	0.7	0.5	-
Whakatane	5	9	10	13	-
Mamaku	7.5	15	6	17.5	-
Rotoma	9	2	13	8	-
Waiohau	11	4	15	-	11
Rotorua	13.5	1	7	4	-
Rerewhakaaitu	15	2	6	-	5
Okareka	18	5	6	-	8
Te Rere	21	10	5	13	-
			Totals	56	29.7
				~85	

Table 3.1 Eruptions at the OVC, 1 – Walker et al. (1984); 2 – Not strictly an intracaldera eruptive, from Cole, 1972.

3.2.1.1 Rerewhakaaitu (15 ka)

The Rerewhakaaitu eruptive episode ended almost 3,000 years of quiescence at the OVC after the Okareka episode (Nairn, 2002) with the extrusion of the Rotomahana dome. After the dome was emplaced, significant pyroclastic flow, fall, and surge activity commenced, and widespread tephra fell over more than 9,000 km^2 (Figure 3.5; Nairn, 2002). The Rerewhakaaitu eruptive episode is thought to have caused major hydrothermal explosions at Kawerau (Nairn and Solia, 1980) and Waiotapu.

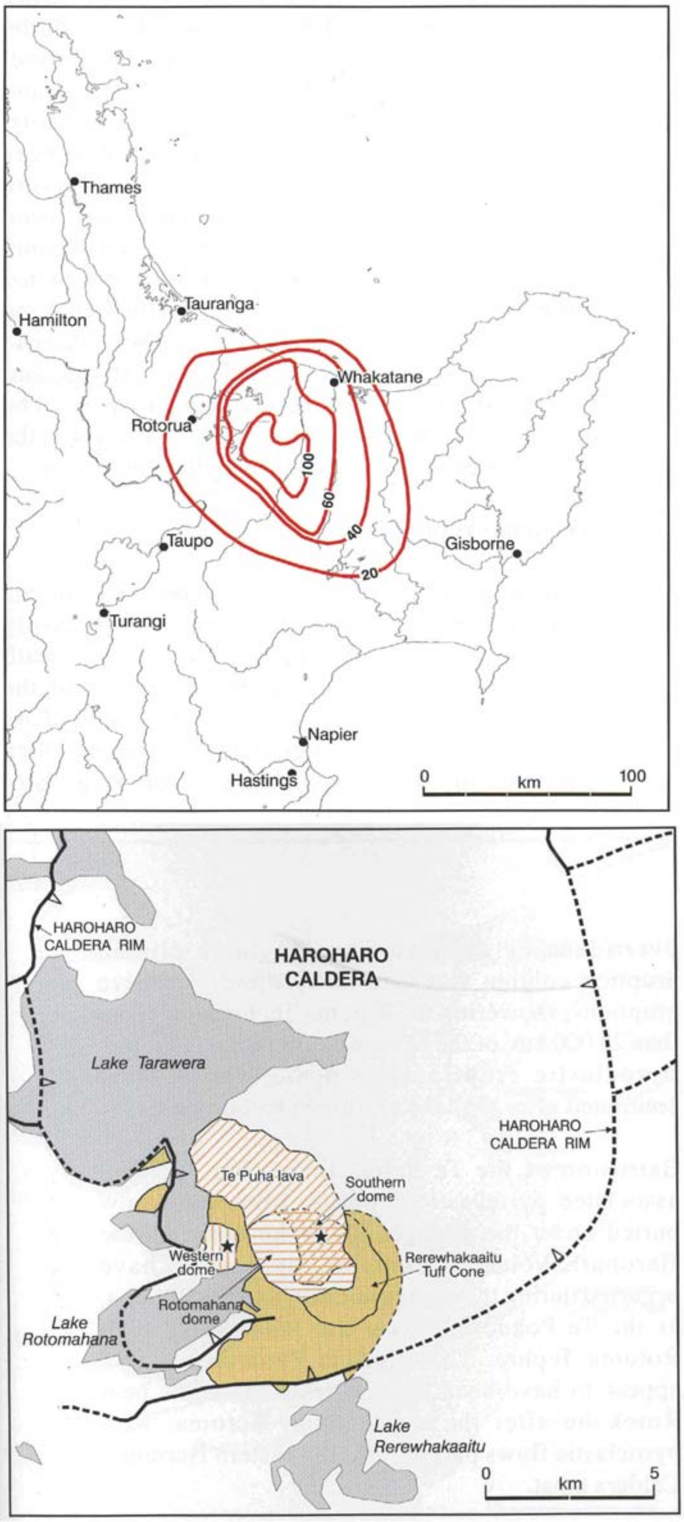

Figure 3.5 Rerewhakaaitu tephra in centimetres (top), lavas (hatched, bottom), and pyroclastics (yellow, bottom), from Nairn, 2002.

3.2.1.2 Mamaku (7.5 ka)

The Rotorua Caldera formed during the 7.5 ka eruption of the 145 km^3 D.R.E. Mamaku Ignimbrite (Spinks et al., 2005, references therein) around three hundred thousand years ago. Milner at al. (2002, 2003) state that the Rotorua caldera formed by one distinct event, not a suite of discrete eruptions. Figure 3.6 shows the distribution of the ~240 k.a. Mamaku Ignimbrite, covering approximately 3,200 km^2 to a depth averaging ~72.5 m (Milner et al., 2003).

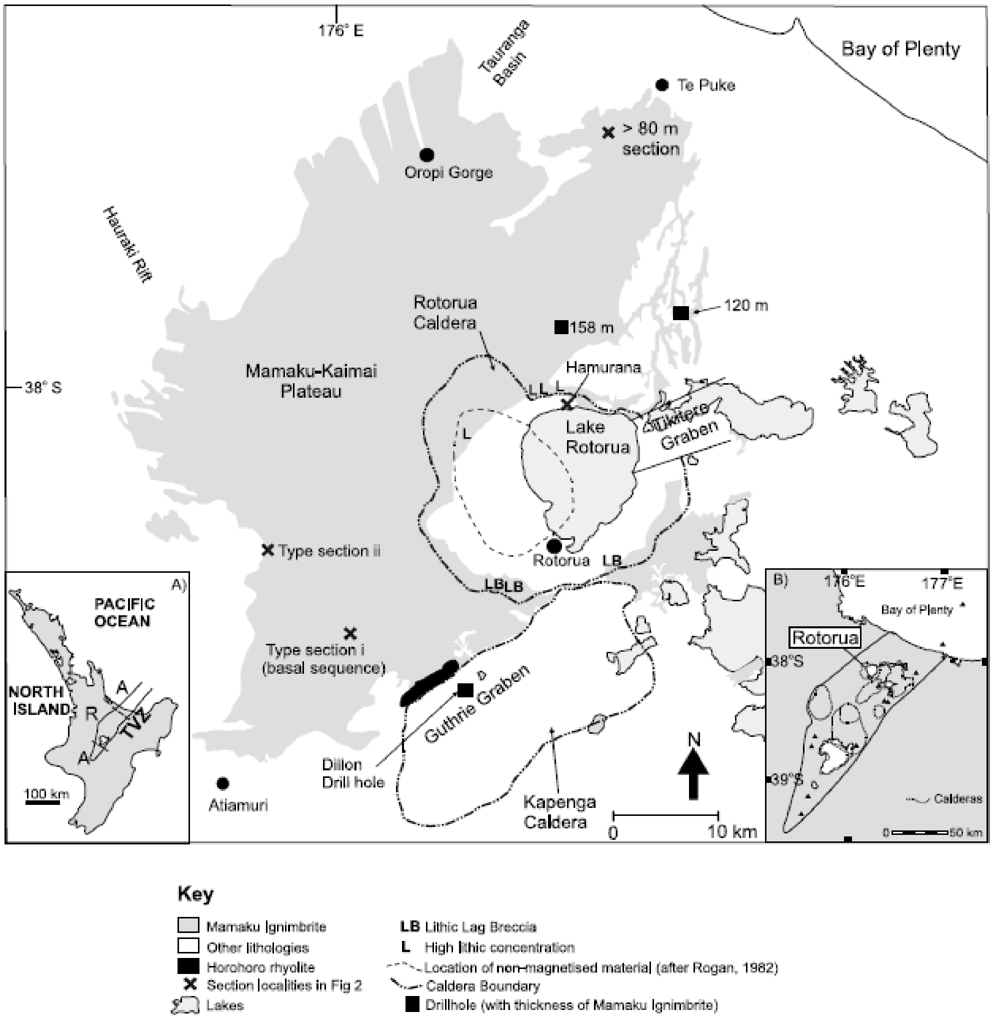

Figure 3.6 Distribution of Mamaku Ignimbrite, from Milner et al., 2003. Rotorua is right and below centre.

Were this event to occur today, a significant portion of the North Island would have to be evacuated, and total and complete devastation would be widespread throughout the Rotorua District and beyond. As an illustration of this point, Rotorua city lies on >1 km thickness of Mamaku ignimbrite (Milner et al., 2003).

As is typical at other large silicic calderas (e.g. Smith and Bailey, 1968; Lipman 1984), several "resurgent" rhyolite domes were extruded after the collapse of the Rotorua Caldera, forming what are now called Mokoia Island and Hinemoa Point (Milner et al., 2002). The eruptions which created these domes would comprise an additional hazardous period of eruptive activity after the main part of the ignimbrite eruption.

3.2.1.3 Whakatane (5 ka)

The Whakatane eruptive episode contained the most recent eruptions from the Haroharo Volcanic Complex within the OVC. Rhyolitic lavas and pyroclastics were erupted over 11 km-length of the Haroharo vent zone from at least 5 vents (Figure 3.7, Nairn, 2002).

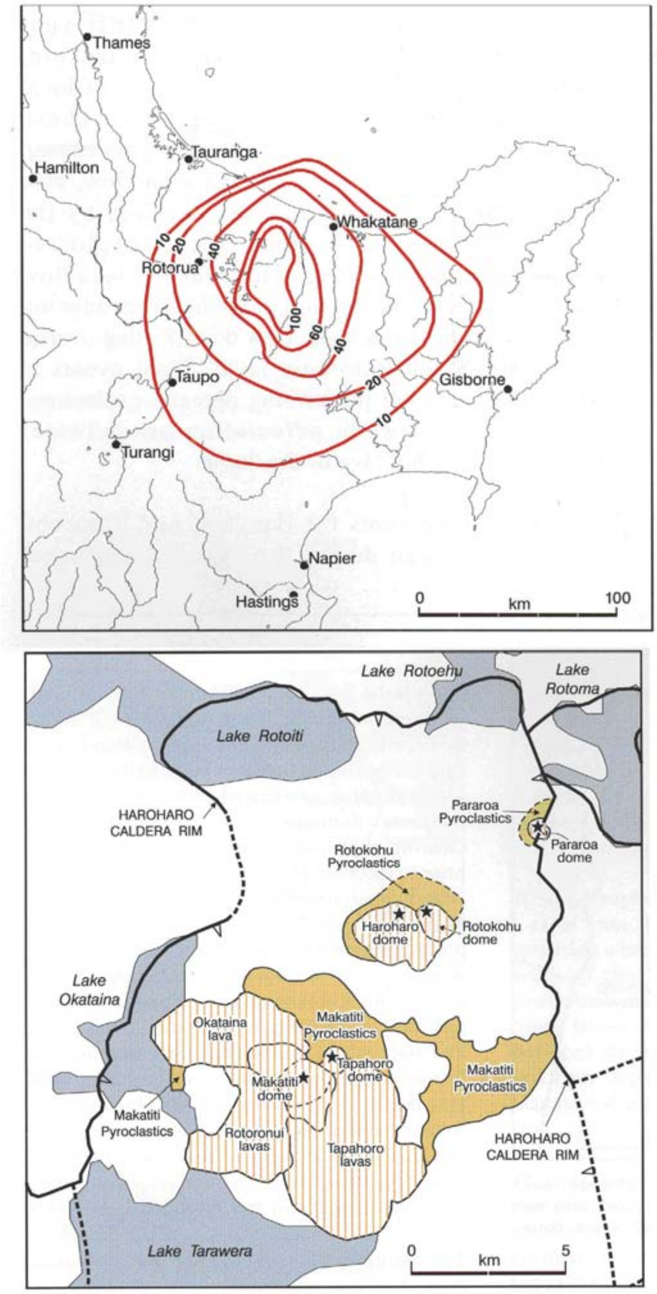

Figure 3.7 The Whakatane eruptive episode tephras (top; thickness in cm), and lavas (bottom - hatched), pyroclastic flow deposits (yellow) and vent locations (stars). Dashed lines indicate uncertain structural boundaries. From Nairn (2002).

The main product of this episode was the Whakatane tephra, which has been mapped over 16,000 km^2 of the central North Island (Nairn, 2002). A variety of deposits were left behind by the varied volcanologic processes at work during this eruptive episode, and an excellent summary is given within Nairn (2002).

3.2.1.4 Kaharoa (0.7 ka / 1314 A.D.)

The Kaharoa eruption predated the arrival of Europeans to New Zealand by at least several hundred years, and was the most significant eruption of any type to have occurred in New Zealand within the last 1,000 years. On the order of 5 km^3 of pyroclastic material and 2.5 km^3 of lava were produced during this episode (Nairn, 2002), both shown in Figure 3.8. The Kaharoa has been studied extensively. Excellent papers exist on its deposits (Nairn et al., 2001), its geophysical precursors (Sherburn and Nairn, 2004), and its causation by basalt triggering (Leonard et al., 2002) to name but a few.

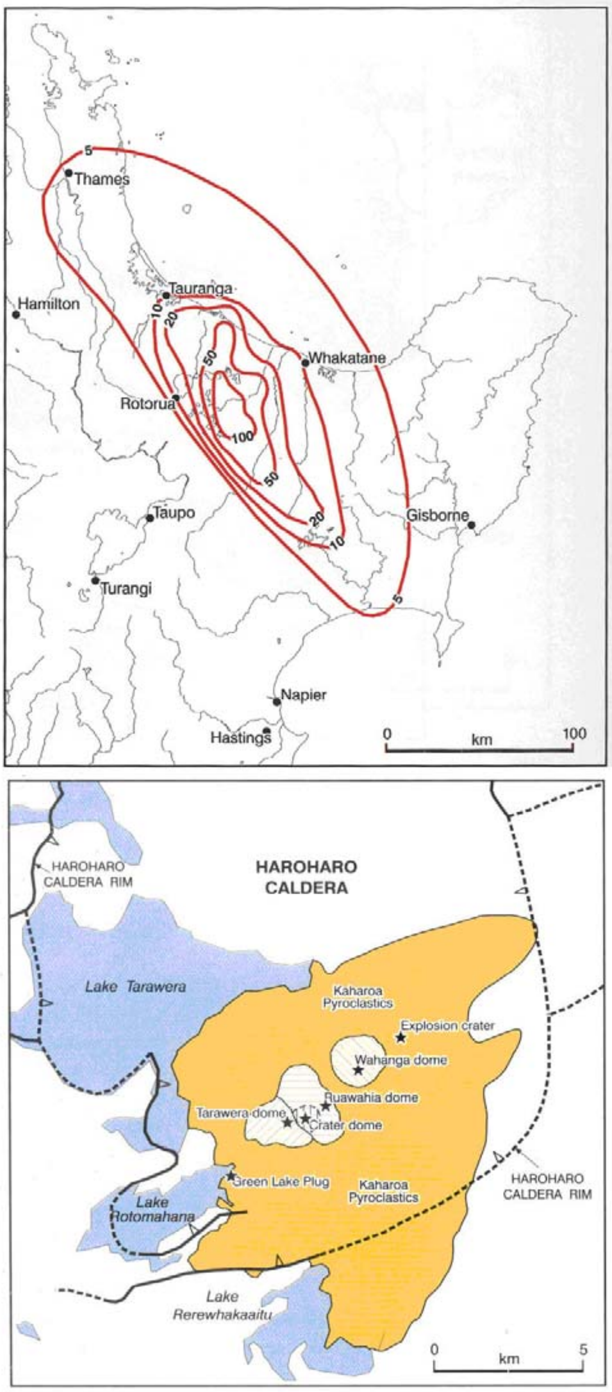

Figure 3.8 Distribution of Kaharoa tephra (a – top; thickness in cm) and lavas (b - bottom), from Nairn, 2002.

Figure 3.8 gives the distribution of the Kaharoa tephra, showing the thickness of the deposit in centimetres. Most of the North Island was blanketed by some amount of tephra from this eruption (Nairn, 2002). At the end of the eruption, the rhyolite domes that comprise present-day Mount Tarawera were extruded. Block-and-ash flows emanated from the margins of these domes as they were emplaced (Nairn 2002), leaving the deposits across the yellow area in Figure 3.8b.

3.2.1.5 Tarawera 1886 Eruption

On 10 June 1886, a fissure eruption began at Mt. Tarawera as a manifestation of the intrusion of basaltic dikes into the Rotomahana hydrothermal system. The major erupted products during this eruption were expelled from a 17-km long, northeast-trending fissure (Figure 3.9) which cut the pre-existing complex of rhyolite domes and extended four kilometres beyond them to the southwest.

Figure 3.9 Aerial view to the northeast of the Tarawera linear rift and vents system. The 1886 eruption began high on the domes comprising the Mount Tarawera massif in the middle ground, forming the fissure seen in the photograph, and extending to the southwest through the short (the paroxysmal stage was but a few hours) course of the eruption (Nairn 2002).

The 1886 eruption produced: a) scoria and ash erupted from the north-western part of the fissure which deposited ~2 km^3 of coarse, moderately-sorted to well-sorted fall deposits (Walker et al., 1984), and b) surge and fall deposits (Figure 3.10) associated with explosions produced from the destruction of the Rotomahana hydrothermal system (Nairn, 1979).

Little to no warning in the form of solfatara or hydrothermal eruptions appeared prior to the onset of this eruptive episode (Nairn, 2002), save for abnormal waves spotted on the surface of Lake Tarawera ten days prior to the 10th June, and felt earthquakes at Te Wairoa and Rotorua beginning at 0030 on the 10th (Nairn 2002).

Some controversy exists as to the exact time at which the eruption began (Nairn 2002), however an in-depth study of the historical record by Keam (1988) places the initial part of the main eruption at ~ 0200 on the 10th June. According to Keam, the expulsion of a large eruption column 9.5 km into the air above the vent marked the eruption's onset. Within the first thirty minutes, a series of craters along the entire Tarawera massif were erupting, shaking the ground for an hour through to 0330. At ~0220, a small eruption occurred from either Echo Crater or Southern Crater at Waimangu, preceding a larger eruption which began at ~0320 through the Rotomahana hydrothermal system, destroying the "eighth wonder of the world," the famous pink and white silica terraces. These phreatomagmatic and hydrothermal eruptions formed massive explosion craters and blasted country rock and juvenile material skyward in an 11 km tall eruption column, which came back to earth in the form of 40 m/sec pyroclastic flows (Nairn, 1979). These flows skipped over the ground surface morphology, overtopping features more than 350 m above the crater floor and coming to rest more than 6 km from their source. Villages at Te Ariki and Moura were wiped from existence, along with camps on the shores of the pre-eruption lakes Rotomahana and Rotomakariri, and buildings at Te Wairoa (see Figure 3.10).

By 0330, the full 17-km long fissure hosted simultaneous eruptions at numerous craters stretching from Wahanga to Waimangu. Voluminous amounts of scoria and tephra were ejected, the latter of which fell on ships lying up to 220 km off the shore in the waters of the Bay of Plenty.

Figure 3.10 Damaged buildings at Te Wairoa from tephra and scoria fall of the “Rotomahana Mud” as a result of the 1886 eruptions (From Nairn 2002). Note the devastated trees in the background, the total collapse of the roof of the mill, and the fresh footprints in the tephra to the right of the back of the mill.

Figure 3.11 shows an isopach map of eruption deposits from this eruption, compiled by A.P. Thomas in July 1887.

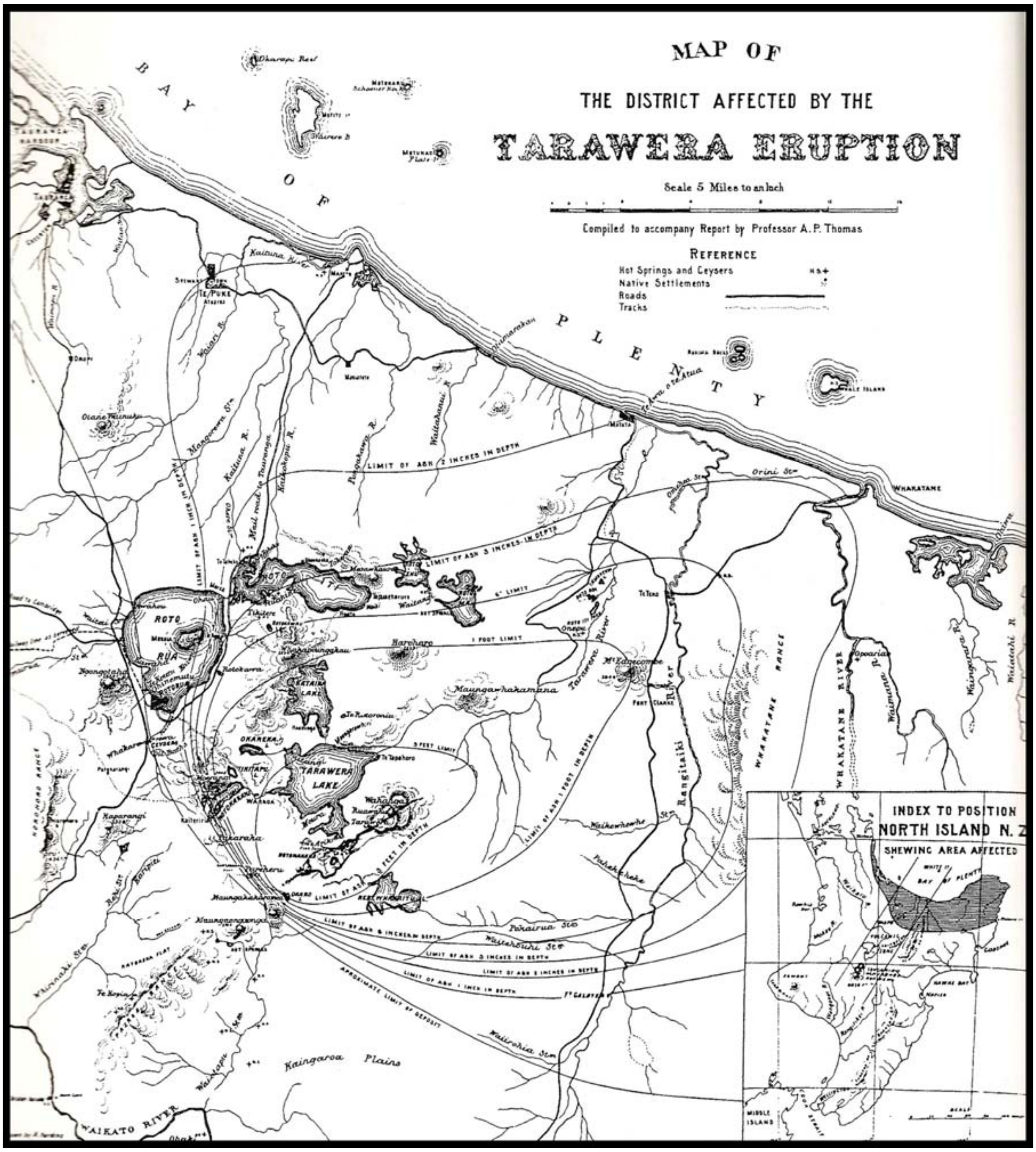

Figure 3.11 Tephra fall isopach map drafted in 1887 (the year after the eruption) by A.P. Thomas, from Nairn, 2002.

Figure 3.12 shows a more recent map of tephra fall, drafted in 1984 by Walker. A range of tephra thicknesses from several meters (such as that shown in Figures 3.10) to trace amounts several hundred kilometres from Tarawera to the northeast were deposited on central North Island (Figure 3.11). This dispersion is due in small part by the geometry of the vent during the eruption (i.e. which direction the tephra was ejected into the atmosphere) and in large part by the southwest (to the NE) prevailing winds in the lower 10 km of the atmosphere during the short few hours following the main eruption.

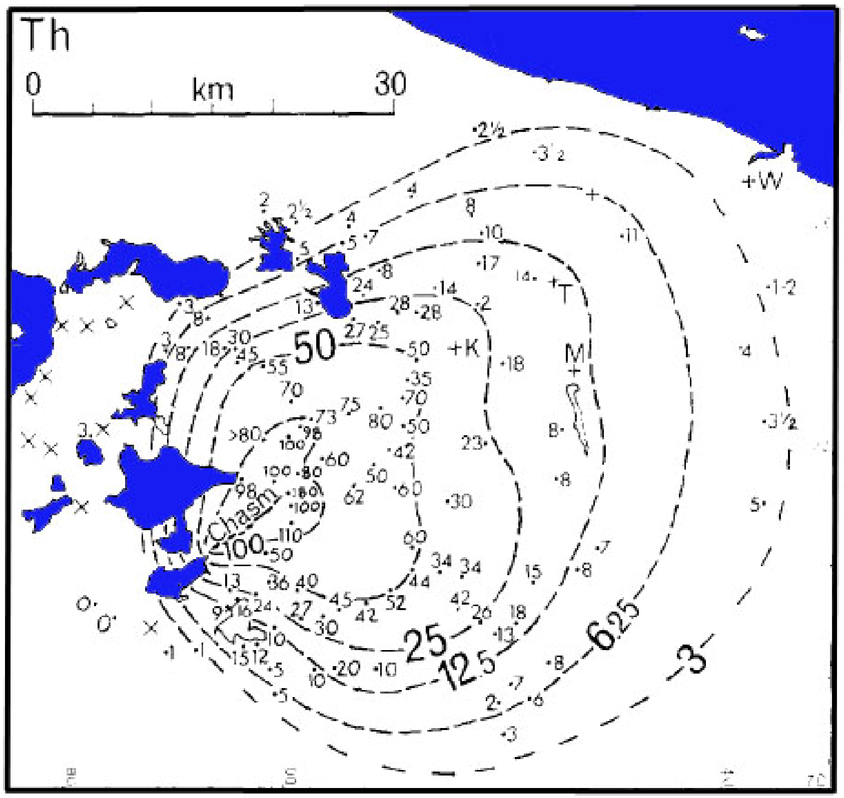

Figure 3.12 Tarawera 1886 scoria fall deposit (thickness in cm). K = Kawerau;M = Te Mahoe; T = Te Teko; W = Whakatane. After Walker, 1984.

Figure 3.13 shows the limit of the proximal base surge deposits emplaced during the 1886 eruption, and the size of the lakes that were present prior to the eruption.

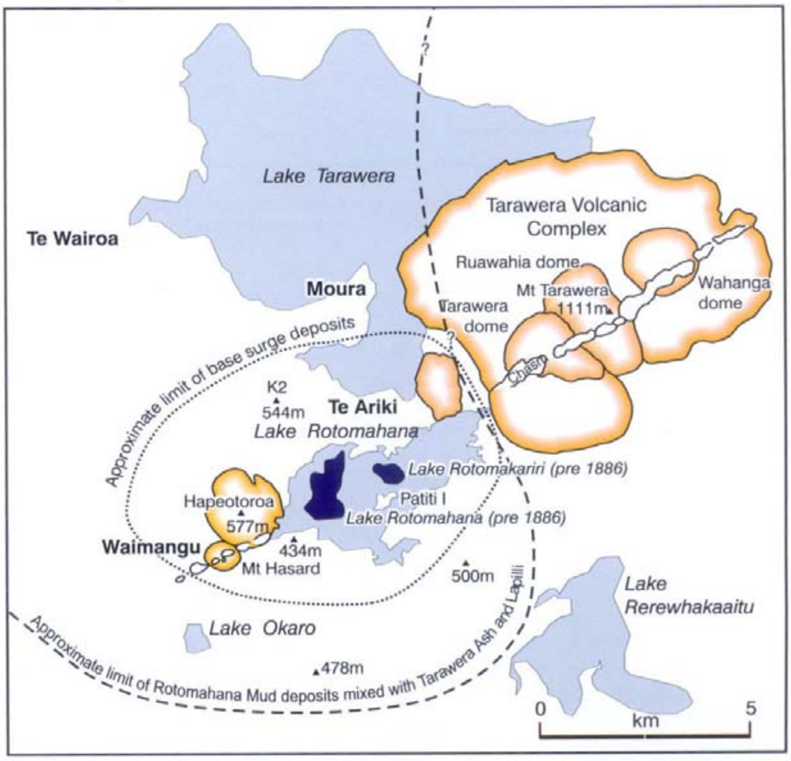

Figure 3.13 Tarawera-Rotomahana-Waimangu area, with pre-1886 lakes and limits of volcanic hazards depicted during the eruption (From Nairn, 2002).

3.2.2 Present-day activity at the OVC

A brief mention of ongoing monitoring of the volcanoes of the Rotorua District is worth mention, as someday it is the hope to integrate this monitoring data into Riskscape. Furthermore, the OVC is very much an active volcanic system, and as such close and careful monitoring holds the key to predicting and understanding future behaviour and potential hazards.

3.2.2.1 Hydrothermal Systems of the OVC

Several active hydrothermal areas lie in or around the Rotorua District. Figure 3.14 depicts these areas.

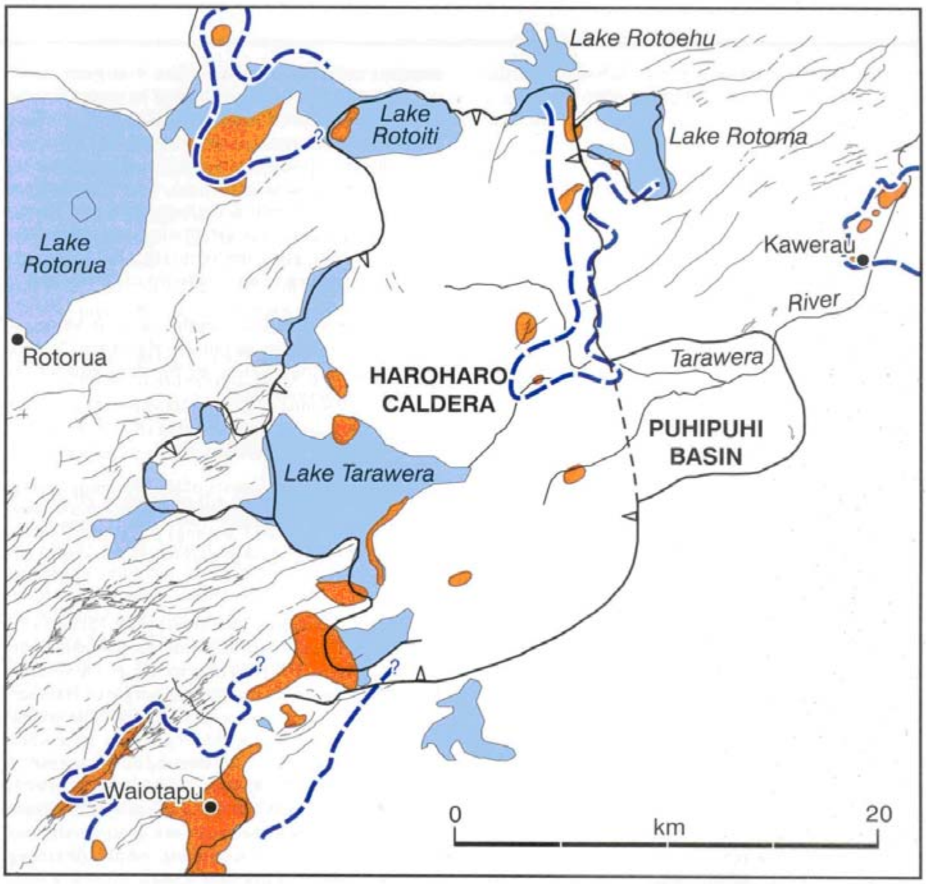

Figure 3.14 Geothermal areas of the OVC, from Nairn (2002). Note the absence of the Rotorua geothermal field in this figure, which underlies several urban areas in Rotorua City and is shown in Figure 3.15. Orange areas indicate surface geothermal expression, and dark blue broken lines indicate areas of low resistivity.

Rotorua City also overlies a geothermal field (Figure 3.15). Eruptions from this field have been frequent in the past few decades. The Rotorua field was first exploited in 1920, and usage soared between 1967 and 1986. Towards the end of this period, natural geothermal features in the area began to dry up, which caused pubic outcry. In 1987, closures began to be enforced, and within one year, water levels raised over 2 m. Over the ensuing decade, activity levels in the geothermal system continued to rebound, although not all pre-development features recovered (Scott and Cody, 2005).

The geothermal systems of Waiotapu and Te Puia area in Rotorua City are iconic features which generate millions of dollars in tourism revenues and are central to the image of Rotorua. Many people do not consciously connect their presence, however, to the fact that their city overlies a potentially degassing body of magma that may one day contribute to future eruptive activity at the OVC.

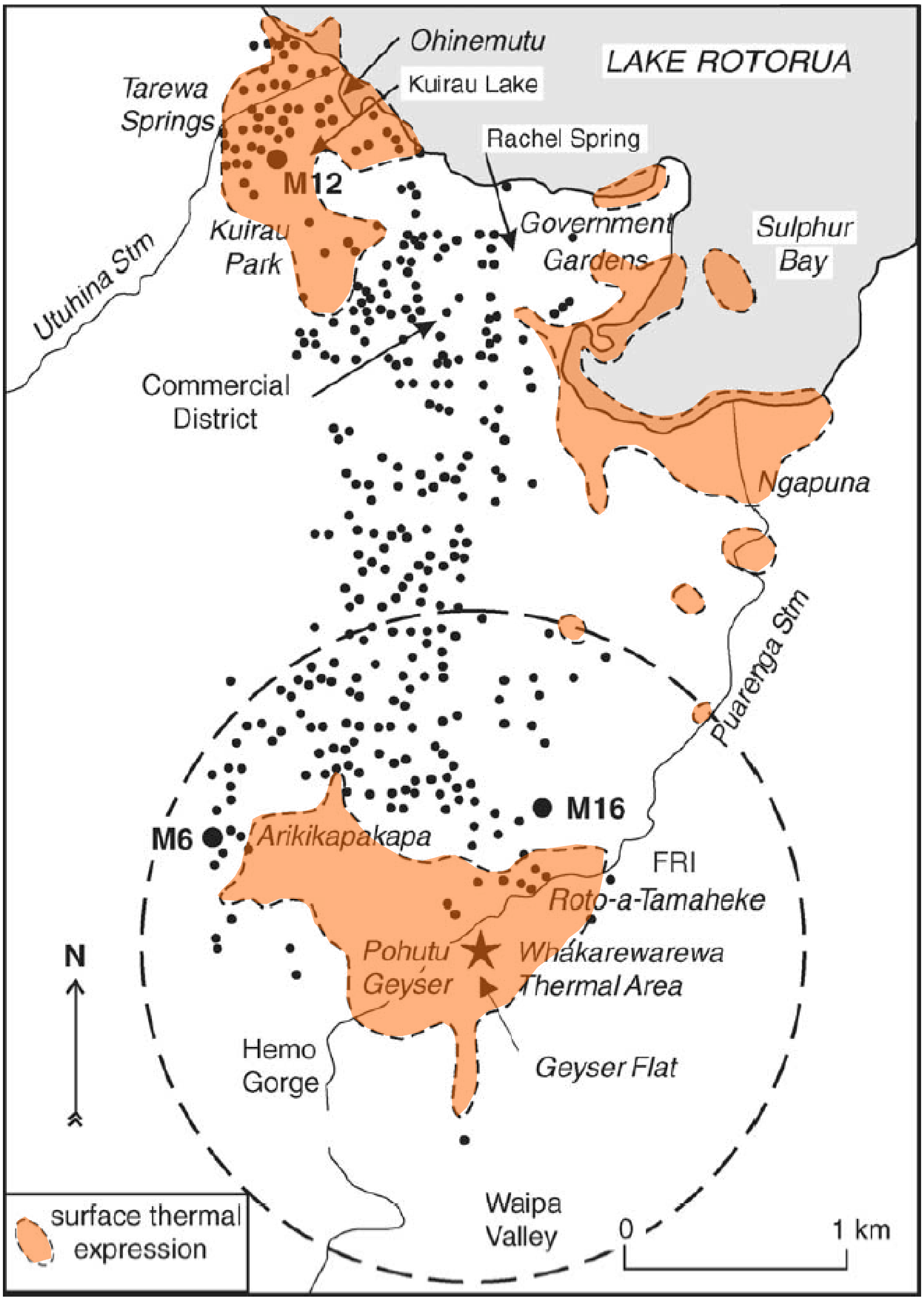

Figure 3.15 Geothermal features (small black dots) in and around the city of Rotorua, which is demarcated by the text "commercial district" to left top. Large black dots indicate monitoring wells, orange shading indicates surface thermal expression. After Scott and Cody, 2005.

4. GEOLOGIC BACKGROUND OF MAMMOTH LAKES AND THE LONG VALLEY CALDERA

The geology of Mammoth Lakes and the surrounding area is dominated simultaneously by the regional tectonics of the Sierra Nevada and the volcanic history of the Long Valley caldera (red line, Figure 4.1).

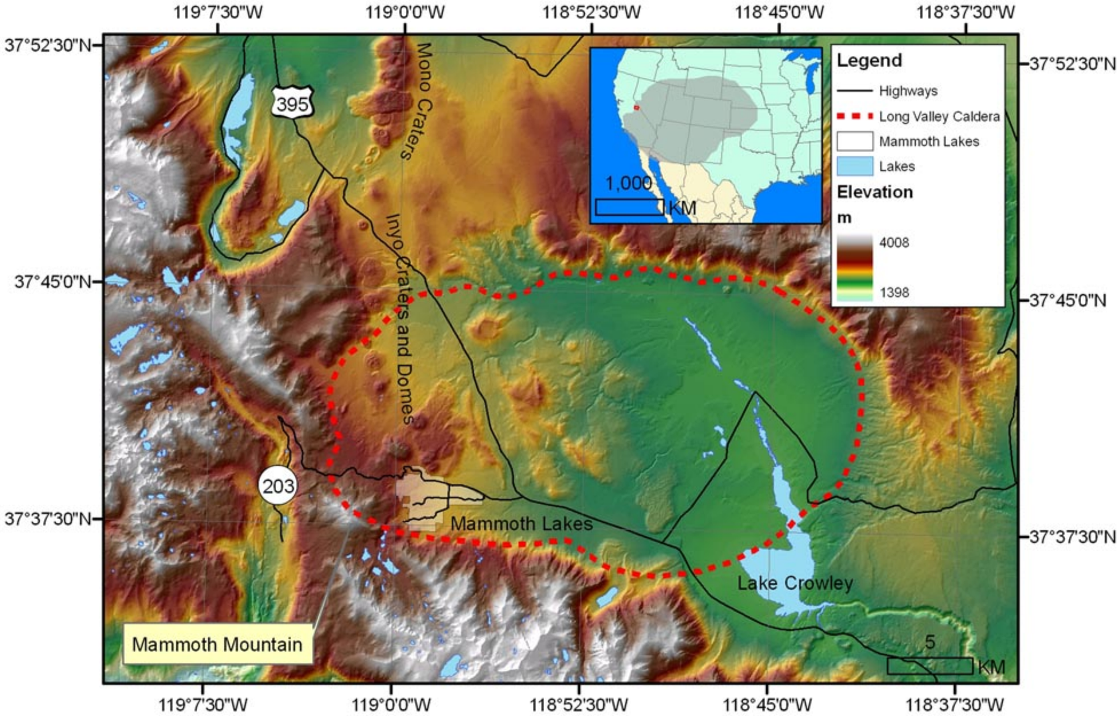

Figure 4.1 Location map of Mammoth Lakes (cream-colored polygon, lower left centre) in eastern California, USA. Inset provides distribution of the ash from the Bishop Tuff eruption, after Izelt et al., 1970.

Mammoth Lakes sits at the southwestern edge of the oval-shaped Long Valley caldera (Figures 4.1 and 4.2) at the base of the eastern limit of the Sierra Nevada mountains and the western edge of the Basin and Range Province. Mammoth Mountain and the 45-km long, north-trending Mono-Inyo Craters volcanic chain (south of Mono Lake, Figure 4.2) compose a late Tertiary to Quaternary complex of volcanic cones, craters, and rhyolite domes, the most recently active of which erupted ~650 years ago (Deadman Creek dome, Hill et al., 1997). Beneath the volcanic rocks in the Long Valley region lie mainly Mesozoic granitic rocks which are either part of the Sierra Nevada batholith or related Mesozoic metavolcanic rocks (Bailey, 1989).

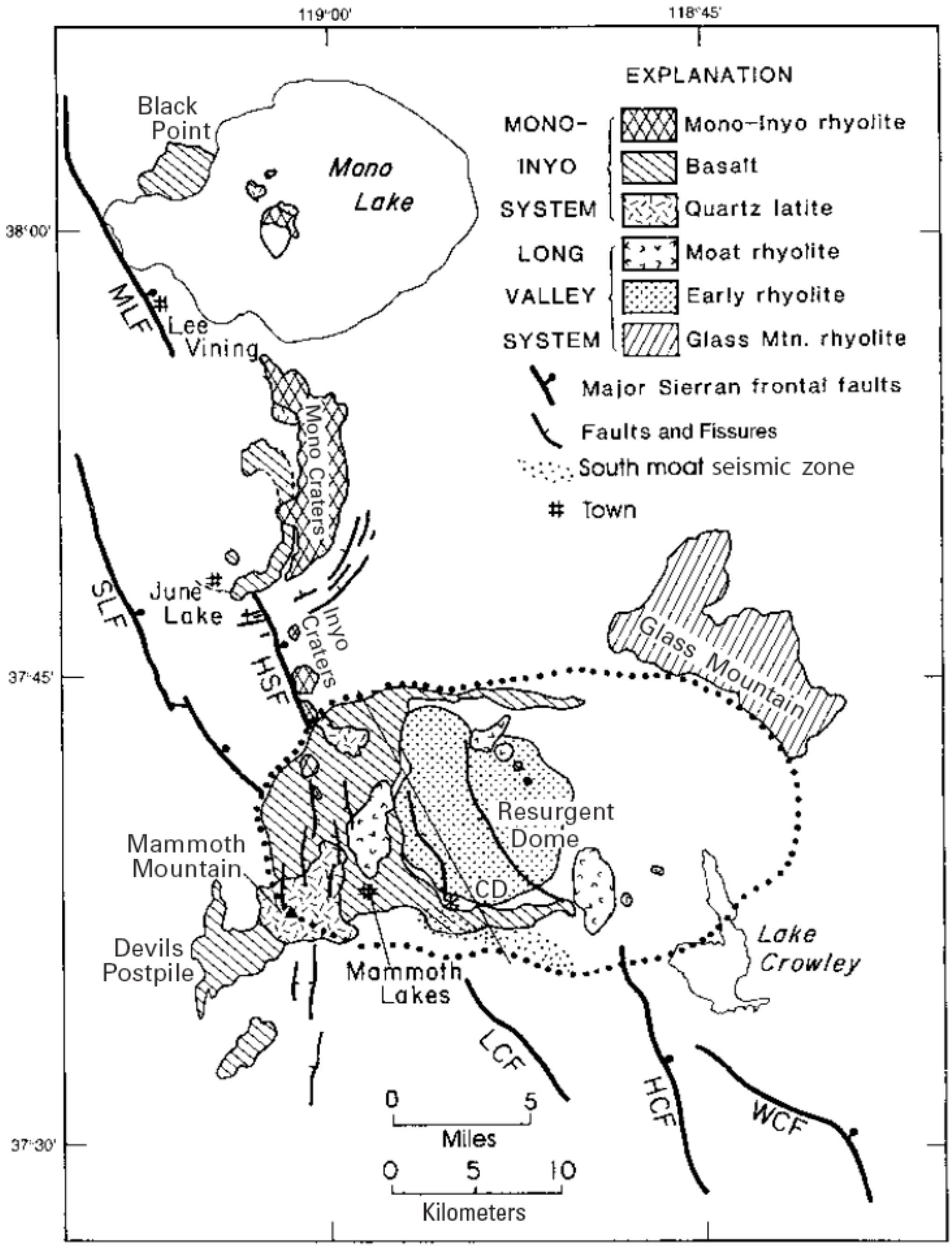

Figure 4.2 Simplified geologic map for Long Valley Caldera and the Mono-Inyo Craters volcanic chain (based on Bailey, 1989). CD, Casa Diablo; HC Hot Creek; HCF Hilton Creek Fault; HSF, Hartley Springs Fault; LCF, Laurel Creek Fault; MLF, Mono Lake Fault; SLF, Silver Lake Fault; WCF, Wheeler Crest Fault. From Hill et al., 2002b.

Volcanism has been present in the Long Valley area since ~ 3.6 Ma, when voluminous amounts of trachybasaltic-trachyandesitic lavas were erupted north of the present-day caldera (Bailey, 1989). Slightly younger basalts were erupted at 3.2 Ma near the north and northwestern rims of the caldera, marking the onset of formation of the magma chamber which would later provide the material for the Bishop Tuff (Kaye, 1997; after Bailey, 1989) which resulted from the caldera-forming eruption of ~600 km^3 of magma 760,000 years ago (Bailey, 1989). The eastern rim of the caldera consists mostly of the high-silica rhyolite domes and flows of Glass Mountain (Figure 4.3), which were extruded between 2.13 and 0.79 Ma (Kaye, 1997).

The Sierra Nevada, which bound the caldera and Mammoth Lakes to the west, are a west-tilted crustal block of 125-80 Ma granite and granodiorite plutons of the Sierra magmatic arc uplifted throughout the Cenozoic (House et al., 2001 and references therein). The Sierra have been heavily glaciated since then, and their eastern rangefront hosts spectacular glacially carved features and valleys such as the world-renown domes and cirques of Yosemite Valley.

Event	Date (Y.B.P)	Deposits	Magma volume	Extent	Key References
Pre-caldera flows	3.6-3.2 Ma	Tertiary volcanic rocks (Tba)	??	4,000 km^2	Bailey, 1989
Caldera forming eruption	760,000	Bishop Tuff	600 km^3	1,000s of km^2 (tephra east to Nebraska)	Bailey, 1989; Bailey et al., 1976)
Mono Craters / Domes	55,000 - 660	High silica rhyolite	5-8.5 km^3	15 km long	Bailey, 1989, Seih and Bursick, 1986; Wood, 1983
Deadman creek dome	682	Rhyolite	>0.13 km^3	80-140 km^2 (tephras); 1.1 km^2 (rhyolite)	Miller, 1985
Mammoth Mountain	111-57 (+/- 2) ka	Rhyolite and Quartz latite flows (Qqm, Qrm, Rrp)	4 (+/- 1) km^3	>25 km^2	Maniken et al., 1986; Bailey et al., 1976 and Bailey, 1989, Hildreth 2004
Inyo Craters	6,000 – 600		0.4 km^3 (lava); 0.22 km^3 (pyroclastics)	16 km long	Hildreth, 2004; Mastin, 1991
Resurgent Dome	Eruption – 0.73-0.65 Ma; uplift – to present	Resurgent dome rhyolites	n/a	~100 km^2	Dixon et al., 1997; Langbein et al, 1995
Tree kills	present	Diffuse CO_2	n/a	1-2 km^2	Sorey et al., 1998, Farrar et al., 1995

Table 4.1 Selected volcanic events at Long Valley Caldera.

Table 4.1 provides selected highlights of the geologic history of the Long Valley Caldera, from just before its formation to the present day. A detailed 1:62,500 scale geologic map and excellent discussion of the area’s geologic history is provided by Bailey (1976 – discussion, and 1989 - map), and the reader is referred to those publications if detailed geologic information is required. The following sections will provide detailed information about events in the history of the area that is significant from the perspective of volcanic hazards in Mammoth Lakes in both the past and potentially the future.

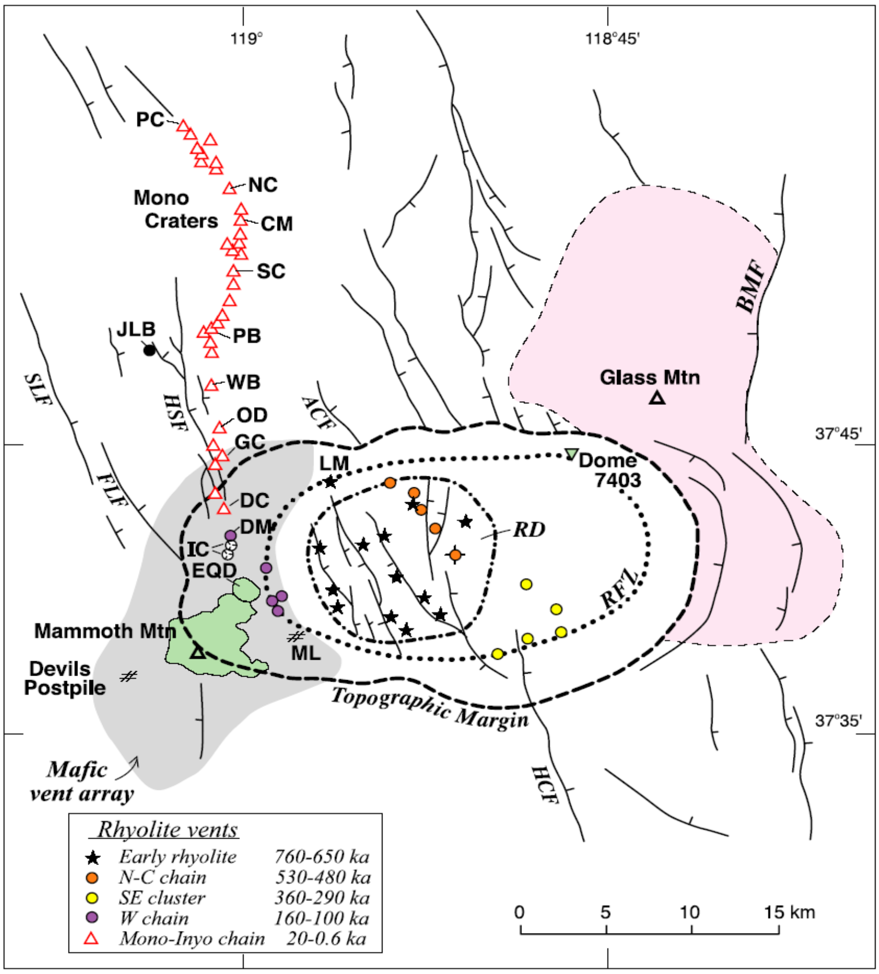

Figure 4.3 Schematic tectonic and volcanic overview map of the Long Valley caldera region, from Hildreth, 2004, after Bailey, 1989. Place–name abbreviations: CM= Crater Mtn; DC= Deadman Creek dome; DM= Deer Mtn dome; EQD= Earthquake dome; GC= Glass Creek dome; IC = Inyo Craters (phreatic); JLB = June Lake basalt vent; LM= Lookout Mtn; ML= Mammoth Lakes downtown; NC= North Coulee; OD= Obsidian Dome; PB = Punch Bowl; PC = Panum Crater; SC = South Coulee; WB=Wilson Butte. Selected faults (after Bailey, 1989) named: ACF = Alpers Canyon fault; BMF= Black Mountain fault; FLF = Fern Lake fault; HCF = Hilton Creek fault; HSF = Hartley Springs fault; SLF = Silver Lake fault.

4.1 Formation of the Long Valley Caldera – the Bishop Tuff

The Bishop Tuff was erupted 760,000 years ago in a paroxysmal eruption that drained over 600 km^3 of silicic magma from the chamber beneath what is now the Long Valley Caldera (Bailey, 1989).

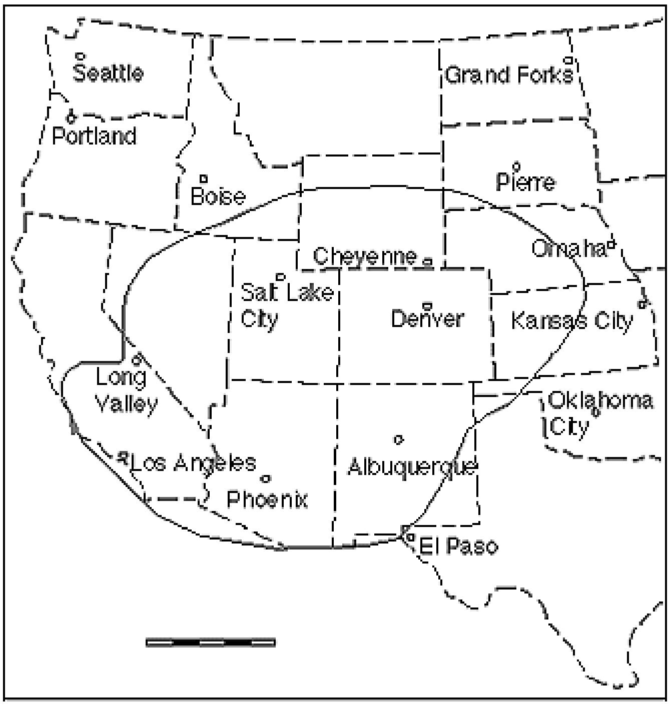

Figure 4.4 Distribution of ash from the caldera-forming eruption of the Bishop Tuff (after Izelt et al., 1970).

The magma chamber, thought to have been ~5 km beneath the surface, drained in a series of eruptions over a continuous eruption lasting around six days (Wilson and Hildreth, 1997). Mafic triggering of the eruption in a similar fashion to that which caused the 1314 Kaharoa eruption at the Okataina Volcanic Centre in New Zealand (Leonard et al., 2002) is thought to have also occurred at Long Valley (Jellinek and DePaolo, 2003). The Bishop Tuff magma was both compositionally and thermally zoned (Hildreth, 2004), and half of it was emplaced outward from the caldera radially in ignimbrite sheets accompanied by plinian tephra and pumice falls. The other half of the magma remained within the topographic depression of the caldera, reaching thicknesses of up to 1,500 m (Hildreth, 2004).

The Long Valley Caldera-forming eruption ranks as one of the largest eruptions known to have occurred on earth (Mason et al., 2004), and is slightly larger than the ~530 km^3 Oruanui eruption from the Taupo Volcanic Centre (Wilson et al., 2006). As with the Oruanui eruption which devastated most of the central North Island of New Zealand, the Bishop Tuff eruption destroyed a huge portion of eastern California, and affected an area of North America spreading across thousands of square kilometres. An eruption of this magnitude has a recurrence probability of 75% within the next 1 Ma, and a 1% probability in the next 460–7,200 years (global probability; Mason et al., 2004). The most recent large rhyolitic eruptive products in the Long Valley caldera are the 100,000 ka Mammoth

Knolls, a series of low hills just north of Mammoth Lakes (Hill et al., 1997). Eruptive activity since then has been relegated to the Mono/Inyo craters and domes.

4.2 Mammoth Mountain

Mammoth Mountain (Figure 4.5) is a ~4 km^3 complex of ~13 exposed (~25-30 in total, including buried domes) trachydacite and alkalic rhyodacite domes and flows (Hildreth, 2004).

Figure 4.5 Aerial photograph of Mammoth Mountain in winter, 2002. The main lodge is at bottom centre, and Mammoth Lakes lies to the left out of the frame. Photo from Mammoth Lakes Community Water District, http://www.mcwd.dst.ca.us/

All of the eruptive features of Mammoth Mountain are geochemically distinct from both the Inyo and Mono Craters and Domes and other volcanic features of Long Valley (Kelleher and Cameron, 1990; Ring, 2000; Bailey 2004). This distinction is significant in terms of future volcanic hazards in that it implies the absence of a connection between the Mammoth Mountain magmatic system and all of the surrounding volcanic features.

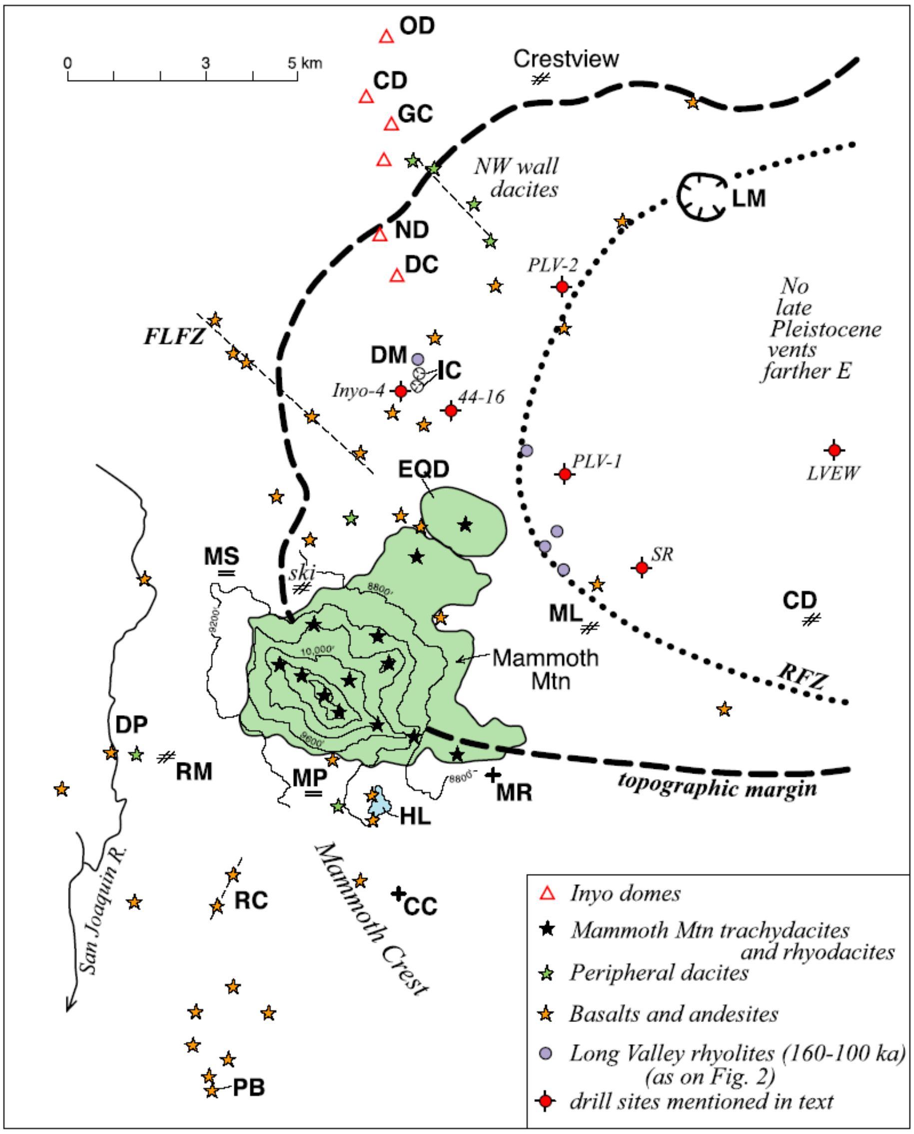

Figure 4.6 Schematic map of Mammoth Mountain and surrounding area, showing volcanic vents in the area. Abbreviations as in Fig. 8.3; in addition, CC = Crystal Crag; DP= Devils Postpile; HL= Horseshoe Lake; MP= Mammoth Pass; MR= Mammoth Rock; MS= Minaret Summit; ND= North Deadman Dome; PB = Pumice Butte; RC = Red Cones; RM= Reds Meadow. Three largest domes of rhyolitic Inyo chain are Deadman Creek (DC), Glass Creek (GC), and Obsidian Dome (OD); two slightly older mini-domes adjacent to GC are Cratered Dome (CD) and a southerly one unnamed.

The line of vents across the summit of Mammoth Mountain trends east-southeast (Figure 4.6, Hildreth, 2004), which lies at a high angle to the lineation of the Mono-Inyo Craters and Domes. This is further evidence for the distinction of the two features. Hildreth (2004) noted that the previously provided age range for Mammoth Mountain eruptive products of 250 -50 ka was erroneously long, and that a range of 111 – 57 ka (both +/- 2 ka) is more likely.

The most recent mafic eruptive feature near Mammoth Mountain (not including the Inyo Craters on Deer Mountain) are the Red Cones, dated at ~8.5 ka (RC, Figure 4.5, Hildreth, 2004). One of the Red Cones is an excellent example of a breached cinder cone with accompanying basaltic lava flows.

4.3 Mono Craters and Domes

The Mono Craters and domes (top left red triangles, Figure 4.3) form an arcuate chain of ~28 phreatomagmatic rhyolite explosion craters and domes just to the south of Mono Lake (Figure 4.7).

Figure 4.7 Aerial view of the Mono Craters, looking south beyond shoreline of Mono Lake (USGS photo by R. von Heune, 1971).

Almost all of the ~5 - 8.5 km^3 of magma which created the Mono craters chain is high-silica rhyolite, and all but four of the features are Holocene in age (Hildreth, 2004). Total lava volume is estimated to be ~4 km^3 (Wood, 1983). The youngest of the Mono craters erupted 660 +/- 20 years ago at the north end of the chain from a 6 km long dike that also produced 0.22 km^3 of pyroclastic airfall and flow deposits, and five distinct lavas including Panum Crater (lowermost large circular crater in Figure 4.7) and North Coulee (Hildreth, 2004).

4.4 Inyo Craters and Domes

The Inyo Craters group of 7 rhyolite domes and several phreatic craters stretch in a straight line north from Mammoth Mountain for ~10 km (Figure 4.8; red triangles, Figure 4.6). The oldest of the craters is the 4-6 ka North Deadman dome, which has a volume of ~ 0.04 km^3 (Hildreth, 2004). The next youngest is 0.05 km^3 Wilson Butte dome of ~1.3 ka, and then the two small (~0.001 km^3) glass domes to the north and south of the large Glass Creek dome were emplaced after Wilson Butte, but before the most recent (~650 y.b.p.) so called “Inyo eruption.”

Figure 4.8 View to the north over the three Inyo Craters and the Deadman Creek rhyolite dome, the southernmost terminus of the Mono-Inyo Craters volcanic chain (USGS photo).

The Inyo eruption caused the emplacement of the Deadman Creek, Obsidian, and Glass Creek domes (in order from oldest to youngest; Hildreth, 2004). Each of these three domes was preceded by substantial pyroclastic flow and fall eruptions, and the total volume of eruptive products produced during this event has been estimated to be 0.4 km^3 of lava and 0.22 km^3 of pyroclastic ejecta (Miller, 1985; Figure 4.9).

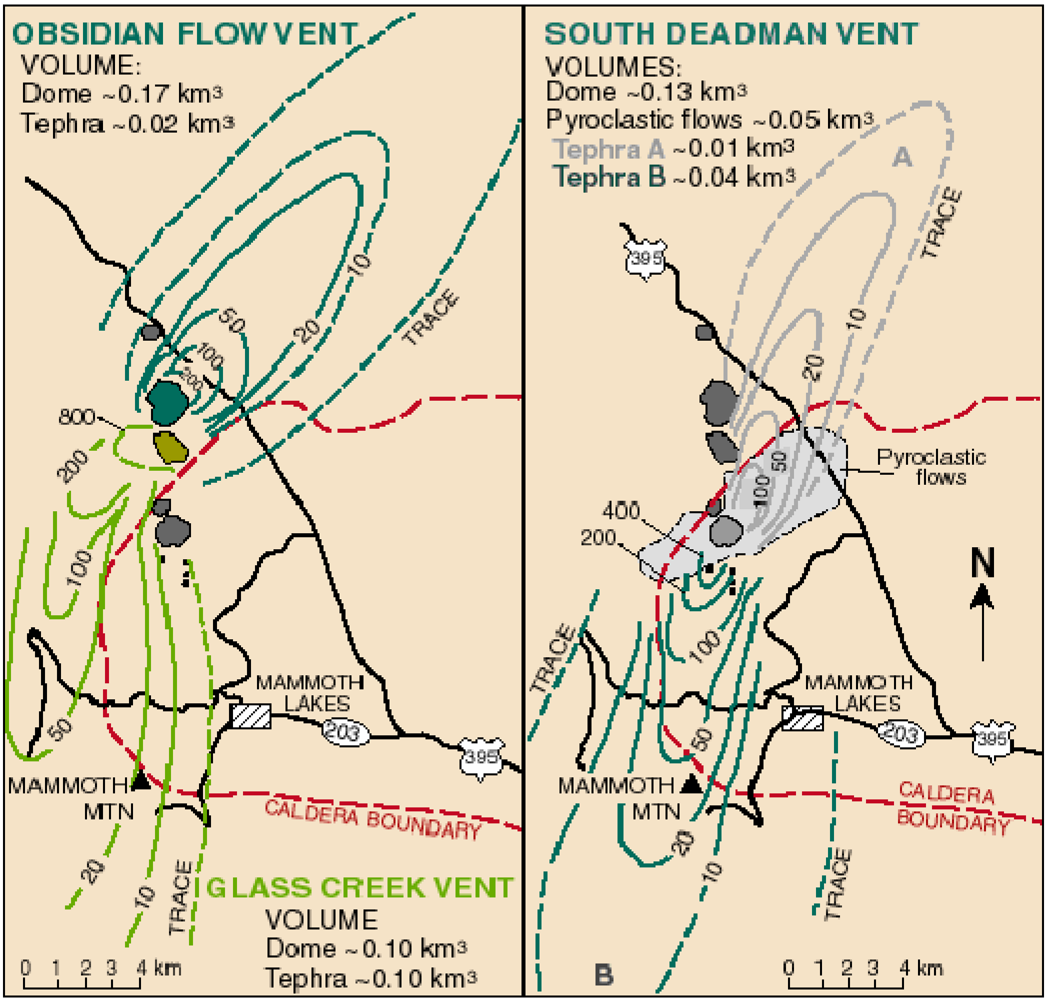

Figure 4.9 Pyroclastic fall and flow deposits from the Obsidian, Glass Creek, and Deadman domes in the Inyo Craters chain just to the north of Mammoth Lakes. Images by C.D. Miller, from USGS LVO Website, http://lvo.wr.usgs.gov, after Miller, 1985.

4.5 Recent activity at the Long Valley Caldera

In the last thirty years, volcanic activity has continued at the Long Valley Caldera. Magma is still thought to underlie the main caldera floor. Geothermal energy from this magma fuels three geothermal plants which generate a combined amount of 40 megawatts of electricity (Hill et al., 1997). In 1978, a period of prolonged unrest began at Long Valley with a magnitude 5.4 earthquake 6 miles southeast of the caldera. Four magnitude 6 earthquakes struck the region on the same day in May 1980 (red stars, Figure 4.10), causing a great deal of worry within the local population.

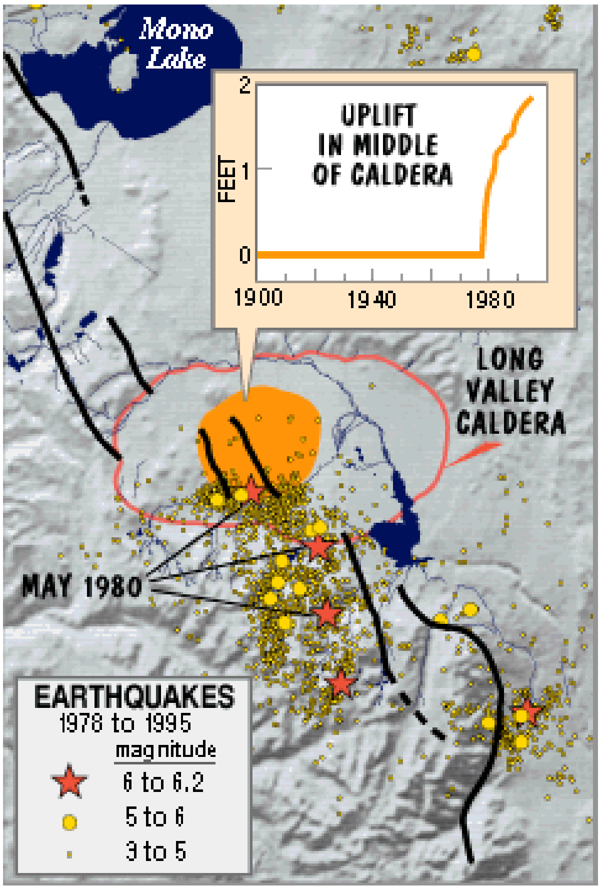

Figure 4.10 Seismicity after 1978 in the Long Valley region (Hill et al., 1997).

The earthquakes led the USGS to intensify its monitoring efforts in the region, and as a result, uplift was detected in the centre of the caldera. The identification of significant, rapid uplift (inset, Figure 4.10) led to extreme public alarm and even death threats to USGS scientists when they went public with information about the earthquakes being potentially related to possible magmatic activity beneath the caldera. Property values in Mammoth Lakes plummeted seemingly overnight, and business at the ski area withered (Mader and Blair, 1987). The unrest continues to this day, but has not yet led to an eruption.

In 1989, a swarm of three magnitude ~3 earthquakes occurred in the shallow upper crust beneath Mammoth Mountain (Hill et al., 1990) as a result of the emplacement of a dike of magma or magmatic brine beneath the mountain (Hill, 2006; 1996). This swarm was contemporaneous with a suite of long-period volcanic earthquakes beneath and near the southwest flank of the volcano (Pitt and Hill, 1994), which occurred at a rate of one to two per month, and are thought to be directly related to basaltic melt propagating through cracks in a zone ~10 to 30 km deep (Hill, 2006).

In 1990, following this earthquake swarm, areas of trees around Mammoth Mountain (~3.6 km^2, Figure 4.11) began to “mysteriously” die. Investigations revealed that unusually high amounts of diffuse CO_2 (~250 metric tonnes per day; Gerlach et al., 1999 and 2001) were being released from depth beneath the dead trees, suffocating them slowly (Figure 4.12).

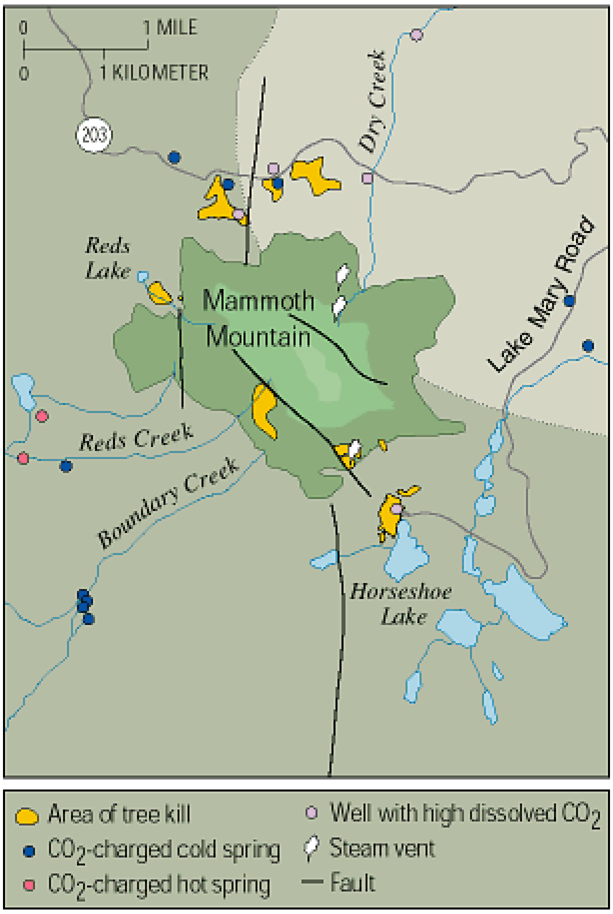

Figure 4.11 Areas of dead trees surrounding Mammoth Mountain (Sorey et al., 1998). The light shaded region to upper right is the approximate shape of the Long Valley Caldera.

The presence of helium isotopes in the gases being released at Mammoth Mountain suggested that the gases were being directly generated from a cooling magma body (Sorey et al., 1998, Farrar et al., 1995), which confirms the active nature of the volcanic systems of the mountain.

Gases are also escaping from the Mammoth Mountain fumarole (white “cloud” shaped polygon at upper centre, Figure 4.11) on the north flank of the volcano within the boundaries of the Mammoth ski area. Rising magmatic gases are occasionally expelled from the fumarole and trapped beneath the heavy blanket of snow which coats Mammoth Mountain in the wintertime. Occasionally, these hot gases melt upwards into the snowpack, but do not reach all the way through. This causes a collapse hazard should anyone venture onto the snow above the fumarole, and the Mammoth ski patrol ropes off the area surrounding the fumarole to prevent members of the public from falling in. Tragically, in the winter of 2006, three ski patrollers who were moving the rope back from the fumarole after a heavy snowfall suffocated and lost their lives when they fell into the fumarole as the snow bridge across it failed (Shirk, 2006).

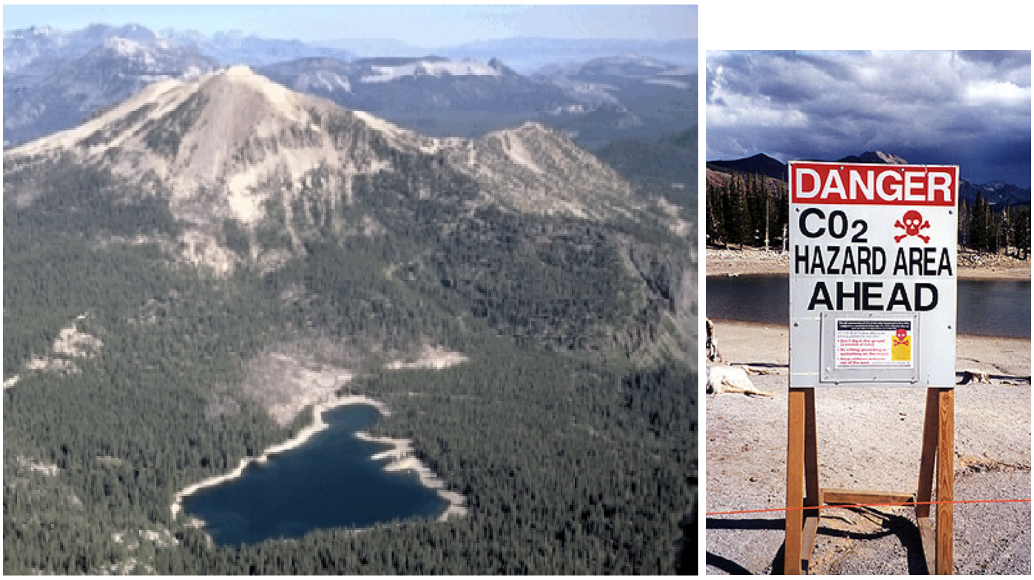

Figure 4.12 Aerial perspective of Horseshoe Lake (left) and the tree kills on its north shoreline behind Mammoth Mountain (USGS photo), and (right) picture of hazard sign located on the shore of the lake.

Uplift, seismicity and diffuse release of magmatic gases in the Mammoth Lakes area are all signs of continued unrest at the Long Valley caldera. As Johnston et al. (2002c) noted, periods of unrest at large silicic calderas can continue for years, even decades, and may or may not culminate in eruption. Although the present state of unrest at Long Valley is relatively insignificant, the potential exists for escalation that could have moderate to even severe consequences to the local economy. The last eruptions near Mammoth Lakes at the Inyo Craters and domes were not that long ago in geologic terms, and the evidence of unrest elsewhere in the Long Valley Caldera suggests that the potential for future eruptions which would impact Mammoth Lakes are worth assessing.

5. DISCUSSION

Each of the publications in this thesis (Chapters 8-14) has its own discussion section. Therefore in order to avoid redundancy, the discussion here in this chapter avoids discussing issues pertinent to each of the individual papers. This chapter therefore has two main parts. The first provides a discussion of the main issues involved with incorporating RiskScape Volcano into RiskScape. This was left out of the RiskScape Volcano GNS Science Report (Chapter 11 / Publication IV) purposefully so it could be placed into this thesis.

The second part of the thesis discussion gives a treatment of overall issues relevant to the entire thesis and its contribution to GIS-based volcanic risk assessment in the context of the goals and research questions presented in Chapter 2.

5.1 Integrating RiskScape Volcano into RiskScape

This section provides a discussion of issues involved in incorporating the RiskScape Volcano model presented in Chapter 11 (Publication IV) into the RiskScape software.

5.1.1 Guidance to the New Zealand Volcanic Hazardscape

If RiskScape Volcano is added into RiskScape, some means of providing the user with guidance to the volcanic hazardscape is necessary. Members of the general public often have a poor understanding of volcanic hazards, due to their typically not having experienced them in their lifetimes (Johnston, 1997). Incorporating guidance to the New Zealand volcanic hazardscape will protect the user from using RiskScape to perform unrealistic risk assessments.

One solution to this issue would be to have volcanologists engineer a comprehensive set of possible volcanic hazard / eruption scenario shapefiles for all major volcanic centres in New Zealand. This could be accomplished by creating a predetermined suite of eruption scenarios and associated volcanic hazards using the literature as a starting point for scenario creation. Once scenarios have been decided upon, they could be made available to the user by a set of pull-down menu choices similar to the historic earthquake menu choices in the New Zealand earthquake model that already resides within the RiskScape software (J. Cousins, GNS Science, *pers. comm.*, 2007). The hazard models could be run in advance to the distribution of the software by volcanologists based on the scenarios in the hazardscape, and the resulting shapefiles made available to RiskScape users via pull-down menus. This is beneficial for the following reasons:

1) Hazard model runs could be done by scientists who have the proper background

knowledge and geologic understanding to generate realistic scenarios and check intensity outputs.

2) Probabilistic consideration could be included in that scenarios could be ordered according to probability, e.g. tephra from 1 in 100 year eruption versus 1 in 10,000 year eruption, etc.

This would also address the issue of including the actual models in the RiskScape software that will be discussed below in Section 5.1.2.

If a set of predetermined volcanic scenarios and hazard maps were packaged with the software, this would add value to RiskScape from the perspective of the end user because the scenarios would be already available and presumably peer-reviewed. Some means of allowing RiskScape users to create their own scenarios would also have to be provided, to allow for user-specific risk assessments.

5.1.2 Integrating RSV Hazard Models into RiskScape

5.1.2.1 Decide Which Volcanic Hazards are Most Relevant

Before the hazard models discussed in Chapter 11 (Publication IV) are imported into RiskScape, some thought on the part of the RiskScape design team should be given to which of the volcanic perils are most important for modeling volcanic eruption risk. In a real eruption, some of the hazards (e.g. tephra and pyroclastic density currents) would probably far outweigh the others (seiche inundation or hydrothermal eruptions) in terms of potential impacts over the greatest area. Further, areas in close proximity to vents are liable to be completely devastated from a combination of hazards.

The suite of models and hazards in Chapter 11 (Publication IV) were chosen from a desire to construct a complete picture of potential volcanic hazards both proximal to and distal from volcanoes, to provide RiskScape with additional hazard modeling capability. Some models are more robust than others in that their output is quantitative (e.g. ASHFALL and EXPLORIS-PDC). Others provide qualitative hazard zones (e.g. seiche or hydrothermal eruption). Some decision needs to be made as to whether it is beneficial to RiskScape to include the qualitative models, or perhaps to group them together and simplify them into distance/damage models with varying binary or step-wise gradational damage rates based on the fragility functions presented in Chapter 11 (publication IV). They are all useful, however, in investigating a full range of proximal and distal volcanic hazards; the argument that they should all be included in some capacity is a valid one.

A decision to simply a) change the wind and volume parameters in ASHFALL, b) incorporate EXPLORIS-PDC into RiskScape to enable PDC modeling, and/or c) investigate implementation of a generic distance/damage model for the remaining hazards would still advance RiskScape's ability to model volcanic hazards from where it presently stands. If the complete set of hazard models presented in Chapter 11 (Publication IV) are not implemented immediately, the information presented in Chapter 11 (Publication IV) still provides a useful review of available volcanic hazard models and fragility functions if the models are to be incorporated at a later date. New models and new function are inevitable, and in the interest of making RiskScape as powerful/accurate as possible, effort should be made by the design team to stay abreast of the state-of-the-art in volcanic hazard modeling even if it means abandoning approaches outlined in Chapter 11 (Publication IV). New models could easily be implemented regardless of their software platform if their outputs were importable into RiskScape Volcano (e.g. shapefiles).

5.1.2.2 Hazard Model Access in RiskScape

Another issue briefly touched upon at the end of Section 5.1.1 is whether to allow users full access to hazard models in RiskScape Volcano, or in other words to actually include the modeling code and software within RiskScape, as is done with the ASHFALL model. This is not advisable for several reasons:

- users might not have the appropriate base data needed to run the models, e.g. the DEM for EXPLORIS-PDC
- users might lack the correct software to run them if they are not already fully incorporated into RiskScape software (e.g. LAHARZ in ArcINFO)
- users might not have the computing power needed to run the models (e.g. the NIWA flood model)
- users might run grossly inappropriate model parameters or place hazards in unlikely locations, e.g. 1000 km^3 eruptions from Auckland or fluid basaltic lava flows from Taupo, or even lava flows in a non-volcanic locale such as Wellington.

All of these points argue for the continued exclusion of RiskScape Volcano hazard models from within the RiskScape software without some means of constraining their application, such as that discussed in Section 5.1.1 above.

The matter of which hazard models to include is also complicated because the choice of which hazards to model is a scenario-based problem. If a rhyolitic eruption were to occur at the OVC or anywhere in the TVZ for example, application of a ballistic ejecta model to estimate damage to houses would be irrelevant in those areas up to ~10 km from the vent as vast areas of the central North Island could potentially be completely devastated (Johnston et al., 2000; 2004) depending on the size of the eruption. This argues again (as in Section 5.1.1 above) for creation of a set of predetermined scenarios.

Also at issue is the intellectual property issue concerning use of the hazard models in commercial

application of RiskScape. The authors of the models that are discrete software (e.g. Paul Cole for EXPLORIS-PDC, apx300@coventry.ac.uk; Larry Mastin for EJECT!, lgmastin@usgs.gov; the US EPA for ALOHA,
http://www.epa.gov/ceppo/cameo/contact.htm) would have to be contacted to discuss application of their models within RiskScape if RiskScape is either sold or used commercially by GNS or NIWA. If the use or output of RiskScape is to be sold for profit, then the inclusion of their models in a commercial version of RiskScape is up to the discretion of the models designers. The RiskScape design team has yet to make this decision (A. King, GNS Science, *pers. comm*., December, 2007), which obviously has a significant bearing on the future of both RiskScape Volcano and RiskScape.

5.1.3 Incorporating Existing Inventory Data

5.1.3.1 Import of Existing Inventory Data for Rotorua

All of the inventory data shapefiles that have been collected for Rotorua can be directly imported into RiskScape for use in modeling risk from other perils, or for volcanic risk modeling so long as ESRI-shapefile capability remains in the software, and permission is obtained from the sources of the data (see Tables 4.1 and 4.2 in Chapter 11/Publication IV).

The Rotorua inventory data were provided by the District Council solely for the Rotorua volcanic risk assessment (Chapter 12 / Publication V), thus it is unclear whether the data can be used for other purposes, and the Rotorua District Council would need to be contacted for permission.

The RiskScape design team has yet to decide whether RiskScape as a finished software will ship with complete inventory datasets (A. King, GNS Science, *pers. comm*., December, 2007), or whether the addition of inventory data will be left to the end users.

5.1.3.2 Import of Existing Inventory Data for Mammoth

It is unlikely that the Mammoth Lakes inventory data would be incorporated into RiskScape at this stage, due to the software's present focus on New Zealand.

5.1.4 Generation of Standard Inventory Dataset for use in RiskScape Volcano and RiskScape

5.1.4.1 Critical Infrastructure – Creating a New Zealand-wide Dataset

To facilitate volcanic risk assessment in New Zealand, a set of baseline critical infrastructure should be established, and then collected for all locations in the country vulnerable to the effects of volcanic activity (all North Island, and South Island within 200 km of Taranaki; Hurst and Smith, 2004). This is not a small task, but it would make RiskScape Volcano as well as RiskScape capable of more uniform risk assessments, especially for large-scale events such as rhyolitic volcanic eruptions. The alternative is continuing to collect inventory datasets piecemeal from a variety of sources when opportunities present themselves, which presents many difficulties, such as data scale and source quality discrepancies, incomplete attributes, and a questionable ability to accurately compare risk assessment outcomes from one location in New Zealand to another.

Deciding what inventory should be included in such a NZ-wide critical infrastructure dataset can itself be a difficult task. The inventory outlined in Table 4.1 in Chapter 11 (Publication IV; critical infrastructure items in the Rotorua inventory) is suggested as a starting point for a critical infrastructure database for RiskScape Volcano. Additional items could include (but should not be limited to):

- Cellular telephone and radio towers / repeaters, especially those that carry emergency services
- Harbour and port infrastructure
- Air travel corridors
- Large-scale foodstuff storage facilities
- Banks, financial centres and other currency depositories
- Computer mainframes that store economic, agricultural, financial, or other critical data.

The onus for creating this dataset should not lie with the creators of RiskScape (GNS Science and NIWA), as accomplishing such a feat would serve all New Zealand government agencies and non-governmental agencies involved in risk assessment research alike. A ministerial agency such as the Ministry of Civil Defence and Emergency Management (MCDEM) would be a much better agency to task with the creation of a critical infrastructure dataset for natural hazards risk assessment.

After deciding what assets should be contained in a national critical infrastructure dataset, one suggested pathway to achieve its creation would be to initiate collection of the data through the Lifelines Advisory Groups from the various regions. These groups could call upon their members to provide the necessary data, provide it to MCDEM, and then MCDEM could process (and maintain) it into one coherent dataset that could be made available to GNS Science, NIWA, RiskScape, MAF, and all other government and non-government agencies involved in risk assessment in New Zealand. New Zealand, due to its relatively small size and cooperative hazards community, could provide an excellent example to the rest of the world by creating a critical infrastructure GIS dataset.

5.1.4.2 Other Inventory

In addition to critical and non-critical inventory, there are several items of "baseline" inventory that would be useful to have for all of New Zealand in RiskScape/RiskScape Volcano for all risk assessment tasks:

1. 10 m (vertical) 25 m (horizontal) hydrologically processed Digital Elevation Model (DEM) or better
2. Slope maps derived from the DEM
3. Bathymetric data for lakes and foreshore
4. Meteorological data, both past and "real-time" for the present (wind, precipitation, tides)

Obtaining these items for all New Zealand is advisable if it has not been already done, although doing so might be difficult due to data ownership and copyright issues.

5.1.4.3 Update and Maintenance of inventory

Inventory data is likely to change over time. Not only will asset values fluctuate, but also the formats and items in inventory datasets will change as more data is gathered, and additional attribute information will likely be obtained for existing inventory. The addition of new fragility functions will also necessitate the collection of more detailed attribute information in order to apply the new vulnerability curves. First-order risk assessment from publicly available inventory information is usually sufficient, however, if the eventual result is relative risk on a regional basis.

The creation and maintenance of metadata as done by Gaspar et al. (2004) in their creation of a comprehensive GIS dataset for geological risk analysis in the Azores, is a crucial step. Care must be taken to retain information about where the data came from, what projection and datum it is in, what quality its source is (e.g. Appendix 2; Chapter 11/Publication IV). Update of inventory databases for natural hazards risk assessment is a costly and time consuming task. Planning for the creation and use of a dataset of critical infrastructure or other inventory must include planning for data and metadata maintenance and updating.

There is no easy way around the complicated issues surrounding critical and non-critical inventory database acquisition and management. Placing the onus of critical inventory collection and database maintenance on a high-level government organisation such as the Ministry of Civil Defence and Emergency Management or the various regional Lifelines groups (e.g. Eastern Bay of Plenty Lifelines Advisory Group) would be an efficient way to ensure that GNS and NIWA staff are free to focus on the scenario / hazard / fragility aspects of RiskScape Volcano (and RiskScape). Doing so would leave inventory collection and management in the hands of agencies who already have mandates to do so.

5.1.5 Required GIS Functionality

If the hazard models and fragility functions in RiskScape Volcano outlined in Chapter 11 (Publication IV) are incorporated at some later date into RiskScape software, in order for them to function as intended, various aspects of the RiskScape Volcano model design require basic GIS functionality in RiskScape. This includes:

1) Import/export of shapefiles, including points, polygons and polylines, maintenance of attribute tables column numbers and names for eventual fragility calculation
2) Import/export of grid data as ESRI format grids
3) Ability to select, clip, and export shapefiles of all types with one another (in other words to create a subset of affected inventory, which is important if an inventory dataset is extensive to cut computational time)
4) Ability to query a grid for values and assign them to points, either from grid cell value or by interpolation
5) Ability to sum the values of a grid over the zone of a polygon
6) Ability to break inventory into small (1 km by 1 km??) pieces if it is excessively larger than the resolution of the hazard model output to enable higher resolution risk assessment.
7) Basic display of one shapefile above/below another in the GUI, ability to change colours and line thicknesses, polygon shading and transparency (this depends upon the decision to enable RiskScape to output risk maps or simply tables).
8) Ability to add raster image data such as aerial photos in variety of formats (GeoTIFF, MrSID, JPEG-W, etc.), this will probably be crucial to end users' ability to visualize risk.

Items 7 and 8 in the above list are aesthetic, and not critical to model function.

RiskScape Volcano will need relatively high-level GIS functionality to operate. Moving RiskScape to an open-source GIS interface such as User-Friendly Desktop Internet GIS (uDig / GeoTools; uDig, 2007) would greatly facilitate basic spatial analysis, such as creating subsets of inventory on the fly, and would also substantially enhance visualisation of multiple layers and enable basic mapping tasks (to create risk maps as an output instead of tables of numerical data). This would also impart RiskScape and RiskScape Volcano with a GIS-functional GUI capable of easily addressing the issues in the above list. Many potential end-users of RiskScape are already used to working with GIS programs such as ArcGIS, so the limited GIS functionality of RiskScape in its present form is likely to detract from the potential user's desire to use RiskScape.

5.1.6 Suggested Menus and Workflow for RiskScape Volcano in RiskScape

This section suggests a set of choices that could be coded together into a menu to work towards making RiskScape Volcano functional in RiskScape. A graphical depiction of the workflow of the model is given in Figure 5.1, based on the steps already in RiskScape. An example flow through these options is given in Table 5.1, below. These choices are circled on Figure 5.1.

FIGURE 5.1 A3 PAGE GOES HERE FOLDED IN

Figure 5.1 Suggested workflow for the RiskScape Volcano model

In this digital copy, Figure 5.1 is in a separate file "fig5.1.pdf"

Category	#	Step	Example
Hazardscape	1	The user picks a volcano, derives an eruption scenario, and decides which hazard(s) to assess risk from	Okataina, rhyolitic eruption, tephra hazards
	2a	The user chooses the appropriate hazard model(s)	ASHFALL
	2b	The user specifies the hazard parameters	5 km^3 tephra (volume), Pukerimu vent (location), wind direction, column height, etc.
	3	The user runs the hazard model	Gives maps of tephra thickness
Inventory	4b	The user chooses an inventory class to assess the volcanic risk to	Critical infrastructure
	4b	The user chooses a subclass, etc. all the way down to specific inventory items (or just a complete class), and ensures that the proper attributes to determine fragility to that hazard	Fire stations (necessary attribute = length of roof span)
Hazard Exposure	5	The user determines what the hazard exposure to inventory with GIS-techniques (combining spatial distribution of hazard intensity map and inventory map)	How thick the tephra is on each fire station
Fragility	6	The user applies the fragility function to determine the damage state of the inventory, including selection of fragility parameters	Rotoma fire station has 500 mm of tephra, roof span falls into fragility class “long”, $D_r = 1$ (example only)
Risk	7a	Risk is determined as percentages of damaged inventory	Five fires stations are damaged 50%, three 25%, and one 100% (example only)
	7b	The user applies the valuation information to determine the financial risk (if desired)	Fire stations are worth $1000/$m^2$, 100 square meters of fire station are damaged 50%, 50 m^2 are damaged 25%, so $ damage is $62,500 (example only).

Table 5.1 Outline of workflow in RiskScape Volcano model. See Figure 5.1 for further detail.

The flow would start with choice of a volcano, then choice of an eruption scenario and appropriate hazard model. The model would then be run, and the output spatial distribution of hazard intensity would be generated. The user would then choose an inventory criticality category, then class and subclass, and then hazard and inventory would be overlapped to determine hazard exposure. Next, the fragility function appropriate to the hazard and inventory item would then be chosen, and applied to the impacted inventory to estimate risk. Value information could then be used to estimate financial damage and thus risk.

As additional inventory sets, hazard models, eruption scenarios, and fragility functions are added, the choices in the menus would have to change accordingly.

5.2 Overall Thesis Discussion

This section discusses issues relevant to the thesis as a whole.

5.2.1 RiskScape Volcano in the Context of the Australia/New Zealand Risk Management Framework

The Australia/New Zealand Risk Management Framework of 2004 (AS/NZ 4360, 2004) is a standard for risk management that applies to both Australia and New Zealand. Government ministries utilise the Framework to ensure that their risk management efforts are of a certain predetermined quality. The ASNZ Framework is given in Figure 5.2, with a broken red box outlining the parts of the framework that RiskScape Volcano provides. The first two steps, establishing the context and identifying the risks prior to undertaking a risk assessment, are achieved through literature review and geologic study of the area subject to risk assessment prior to the initiation of the RSV model (understanding of the hazardscape).

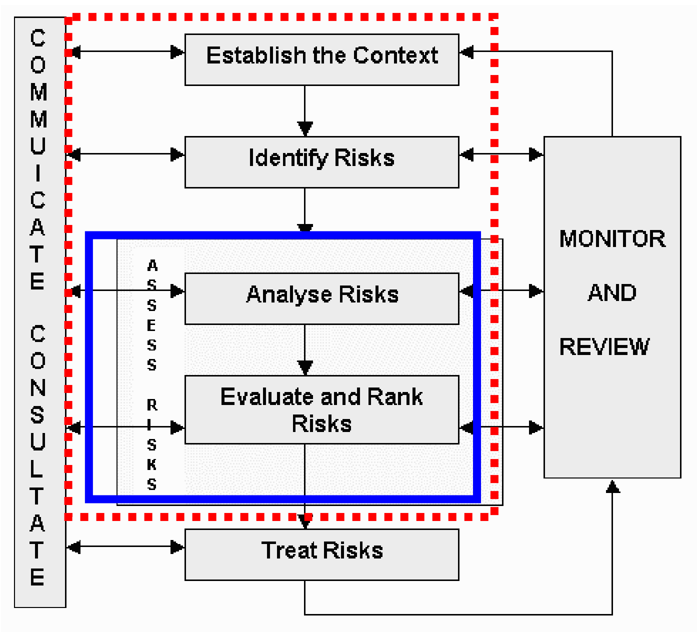

Figure 5.2 Risk management from the AS/NZ 4360:2004, modified to show the portion of the model that RiskScape Volcano provides (red dashed line, with technical portion indicated by solid blue line).

The solid blue box in Figure 5.2 encloses the technical aspects of the risk management framework provided by RiskScape Volcano when undertaking risk assessment of volcano hazards – analysis and evaluation of risks. The RiskScape Volcano model does not implicitly rank risks, but subsequent runs of the model that examine different hazards or scenarios could be used to generate a risk ranking outcome.

The last step in the AS/NZ framework, treatment of risks, is represents an extension of the work done by RSV and presented in this thesis. This extended work would branch out into related scientific disciplines such as sociology and psychology to develop risk mitigation strategies. Risk assessments, if done in a way that effectively communicates risk to targeted audiences (either public or government), can be a powerful treatment of risk.

Some of the work done as a part of this thesis, however, would be useful when preparing and evaluating the effectiveness of risk treatment in Mammoth Lakes, for example. Chapter 14 (Publication VII), provides a baseline understanding of hazard awareness in Mammoth Lakes in the tourism sector. After publication and distribution of a risk assessment such as that given in Chapter 13 (Publication VI), a follow-up survey could be conducted in Mammoth Lakes to assess the effectiveness of publishing a risk assessment as a strategy to treat risk.

5.2.2 The Effects of Risk Assessment Outcomes and Effective Risk Communication.

Risk assessments should not be done without considering their outcomes. As was reported in Mader and Blair (1987), the mere mention in the *Los Angeles Times* of possible volcanic hazards in Mammoth Lakes in the 1980s led to severe drop in property values and threats to USGS scientists. In that case, the USGS scientists did not effectively communicate the potential for volcanic risk along with their actual assessment of the risk. This should be avoided in the future.

Effective risk communication is essential in any risk assessment with RiskScape Volcano. Risk assessments need to be accompanied with information that puts them into context in terms that the targeted audience can understand. The easiest way to do this is to present hazards scenarios simultaneously with information describing their probability in a way the public can understand, such as was done in the Rotorua Risk Assessment (Chapter 12 / Publication V) in Section 5.6 by comparison of the odds of dying in a car accident in the US with the annual chance of an eruption in Long Valley. Ineffective risk communication is an irresponsible use of the RiskScape Volcano model.

5.3 Application of RiskScape Volcano Outside of New Zealand

As demonstrated by Chapter 13 (Publication VI), the RiskScape Volcano model can be applied outside of New Zealand. The collective nature of the model as a sum of different parts allows it to be easily ported to any location where the user has an understanding of the hazardscape, hazard models appropriate for the scale and character of hazards, pertinent inventory databases, and fragility functions for the inventory and the hazards. The steps of the model as outlined in Chapter 11 (Publication 4) are not New Zealand- (or Mammoth Lakes-) specific, and would not change if the model were to be applied in Indonesia, for example.

The power of the RiskScape Volcano model in its present form is that it is simply a set of procedures in ArcGIS and Excel, which lends the model portability and flexibility. The model could be obtained and implemented by anyone, and also customized or modified by them any number of ways to better suit their particular risk assessment needs. In this way, RiskScape Volcano advances efforts in volcanic risk assessment by providing a coherent set of procedures for quantifying risk to inventory from volcanic hazards.

5.4 Advancement of GIS-based Volcanic Risk Assessment

Table 1.2 showed a portion of the large amount of work that has been done in New Zealand to assess volcanic risk. When compared to other natural hazards such as earthquakes, however, quantitative physical vulnerability from hazardous volcanic events is poorly modelled for the following reasons, after Douglas (2007):

1. the cause of human casualties from actual volcanic hazards rather than building damage is rarely differentiated
2. a lack of observational data exists on:
    a. the hazard
    b. the elements at risk
    c. the induced damage
3. the complexity of the structural damage mechanisms
4. the temporal and geographical scales
5. the ability to modify the hazard level by removing people and assets.

Typical risk assessment with hazard maps is qualitative (low to high). Douglas (2007) notes that this kind of risk assessment provides guidance as to increasing levels of risk, but cannot provide quantitative estimates of direct economic loss.

Earthquakes cannot be prevented or predicted, nor can ground shaking be reduced. Also, there is no advance warning for dangerous seismic events, and therefore there can be no evacuation. In order to manage the risk from earthquakes, levels of exposure and vulnerability must be lowered by safer land use planning and updates to building codes or retrofitting structures in earthquake prone areas (Douglas, 2007).

One effective way to achieve a similar mitigation of volcanic risks is via better understanding of volcanic hazards and their potential impacts on inventory and populations. RiskScape Volcano advances this effort by providing a working model for quantitative physical vulnerability assessment that collects all the necessary parts in one model. Although effective, it has its share of limitations (see Section 8.8; Chapter 11 / Publication IV).

5.4.1 Limitations of Understanding the Scope of Thesis

Until RiskScape Volcano is incorporated into RiskScape, RiskScape will not be fully able to model a complete suite of volcanic hazards. When the two are combined, the possibility exists that some aspects of RSV might not be implemented in RiskScape (see discussion above in Section 5.1.2). Because the incorporation of the models is actually beyond the scope of this thesis, it is difficult if not impossible to discuss the effectiveness and scope of the finished product. In terms of providing the RiskScape development team with a functional GIS-based volcanic risk assessment model, this thesis has achieved its primary goal.

6. CONCLUSIONS

This thesis presents a new model for scenario-based volcanic hazards risk assessment: RiskScape Volcano. RiskScape Volcano was conceived and designed for eventual inclusion in the RiskScape software to allow the software to be able to more completely model risk from a full suite of volcanic hazards (proximal and distal) in New Zealand. The model was tested in Rotorua, New Zealand, and Mammoth Lakes, California.

The first seven research questions posed in Chapter 2 are answered in the conclusions of each of the seven publications that comprise the second half of this thesis. Regarding the remaining research questions:

8. The flow through the RiskScape Volcano model mirrors the flow through the RiskScape model. This is intended to facilitate easy incorporation of RSV into RiskScape.
9. Figure 5.1 gives a proposed design for the RiskScape Volcano model for when it is incorporated into RiskScape.
10. The major issues involved with incorporating RSV into RiskScape are:
    a) Deciding upon a set of scenarios within the NZ volcanic hazardscape, conveying them with a sense of probability to aid end users in performing realistic risk assessments
    b) Deciding which hazards models to incorporate, obtaining permission from their creators
        1. This is partly contingent upon the outcome of the decision on whether RiskScape is to be free or to be sold.
    c) Deciding how to provide access to hazards models in RiskScape
        1. If incorporated, some hazard models would need to be reprogrammed to enable them to function in a Java-based environment
        2. If not incorporated, it is suggested to use a suite of eruption scenarios to pre-compute a range of hazard model outputs and make them available to RiskScape users via pull-down menus
    d) Adding GIS functionality into RiskScape to facilitate hazard exposure determination
    e) Creating a NZ-wide set of critical infrastructure data
    f) Generating new fragility functions to match new inventory
11. RiskScape Volcano advances the field of volcanic risk assessment by providing a comprehensive GIS-based volcanic risk assessment model that includes hazard models, inventory maps, use of GIS to assign hazard exposure to inventory, and fragility functions to estimate risk. When decisions are made regarding the

incorporation of RiskScape Volcano into RiskScape, and the two are combined, then a greater sense of the contribution of this work towards advancing the field of volcanic risk assessment will be known.

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8. PUBLICATION I – MERAPI GNS SCIENCE REPORT

“Impacts of the 2006 eruption of Merapi volcano, Indonesia, on agriculture and infrastructure”

GNS Science Report (2007/07)
By Tom Wilson, Grant Kaye, Carol Stewart, and Jim Cole
64 pages
ISSN 1177-2425
ISBN 0-478-09-970-3

8.1 Specific Contributions of Mr. Kaye to the Report

The Merapi report, along with the field work on which it was based, was a collaborative effort between Mr. Kaye and Mr. Tom Wilson. Although the project was conceived and undertaken as a collaborative effort from the very beginning, the research focus was divided in that Mr. Kaye led investigations into infrastructure impacts, while Mr. Wilson examined the effects of the eruption on agriculture. Prof. Jim Cole provided discussion and some editing and is recognised as an author to signify his role as the primary PhD supervisor of Mr. Kaye and Mr. Wilson. Dr. Stewart provided technical editing of the manuscript.

Work in the field at Merapi was shared evenly by Mr. Kaye and Mr. Wilson. This included collecting ash samples, recording GPS points of field stops, talking to local residents, administering a field budget, making arrangements for field transportation and interpretation, taking photographs and field notes, and setting up visits at local universities. Chapters 1 and 2 were written in collaboration with Mr. Wilson, while Mr. Kaye wrote chapters 4, 6, and 8. Chapter 9 was written by both Mr. Kaye and Mr. Wilson. Mr. Wilson authored chapters 3, 5, and 7. Mr. Kaye performed all of the GIS work undertaken to prepare and draft most of the map figures in the science report, specifically Figures 1, 3, 6, and 14. Mr. Kaye also organized and processed all the photographs taken at Merapi, and prepared them for use as figures in the paper. Editing responsibilities were shared evenly by Mr. Kaye and Mr. Wilson (each edited the other’s chapters), along with editorial contributions made by the other authors, mainly by Dr. Stewart.

9. PUBLICATION II – AGRICULTURAL FRAGILITY FUNCTIONS

“Agricultural fragility estimates for volcanic ash fall hazards”

GNS Science Report (2007/37)
By Tom Wilson and Grant Kaye
51 pages
ISSN 1177-2425
ISBN 978-0-478-19603-0

9.1 Specific Contributions of Mr. Kaye to the Report

This publication was essentially authored in even amounts by both Mr. Wilson and Mr. Kaye, both of whom collaborated on nearly every aspect of the work. Some aspects of the work were led by one author: Mr. Kaye led the establishment of the theoretical framework for the paper (Section 2.0) because his primary research was more involved with RiskScape than Mr. Wilson’s. To the same effect, Mr. Wilson led the establishment of the agricultural impacts section (Section 3.0), but both authors worked in concert to create the fragility functions. Mr. Wilson brought his expertise in agriculture (e.g. Wilson and Cole, 2007), while Mr. Kaye brought his expertise in GIS and fragility function design, as well as familiarity with the design requirements of the RiskScape program.
Editing was accomplished equally by both authors in turn. In almost all respects, the paper is an even collaborative effort between Mr. Wilson and Mr. Kaye.

9.2 Corrections and Additions to Publication

9.2.1 Differences in Ash Thickness vs. D_r for Different Crop Types

The differences in ash thickness versus damage ratio exhibited for the different crop types depends largely upon the way in which the authors envisaged each crop would withstand and resist damage from a fall of a similar amount of volcanic tephra. This is due to the different morphologies of the different crops – some are leafy, some grow their commercially viable parts underground, some grow on trees, some are fruits, some have hard skins, etc. The various physical characteristics of the crops are the main determining factor in predicting the amounts of damage done by the same amounts of tephra.

Providing a more detailed explanation of each crop type is beyond the scope of this addendum, and merits a wholesale update and re-write of the publication.

9.2.2 Fragility Function Shape

The majority of the fragility function curves for crops in this report (e.g. dairy, sheep, and beef losses in Figure 9) show accelerating losses. This means that the damage increases at an accelerating rate as tephra thickness increases. Most curves reach a threshold of tephra above which the loss curve asymptotes to 100%.

Peculiar shapes in some curves, such as the pastoral farming asset loss function in Figure 9, are due to an amount of resilience being built into the curve from the point of initial tephra accumulation, but not through the entire range of tephra thickness. Above a certain amount of tephra, the resilience disappears, and then damage proceeds with a linear relationship existing between damage and tephra depth. Above this point, the loss then accelerates (see also inflection points in seasonal and permanent horticulture asset curves in Figure 12).

Some curves show a high degree of resilience at low levels of tephra accumulation, in that damage occurs slowly up until a certain threshold is reached. One such curve is that given for root vegetables (Figure 11), whose main commercially valuable portion remains underground until the time of harvest. This crop has a high amount of resilience from damage by tephra, manifested by a very slowly accelerating fragility function at low amounts of tephra.

In general, the shape of the curves are meant to depict the transition of the relationships between accumulated tephra thickness and damage as that thickness goes from zero to significant amounts of tephra.

9.2.3 Preliminary Nature of Fragility Functions

It is important for the reader of this report to bear in mind that the fragility functions presented in this science report are preliminary. The functions are based on:

1) Observations made in Indonesia during the 2006 eruption of Merapi volcano (Publication I), with modifications made to reflect how tephra would impact crops in New Zealand;
2) Experimental laboratory and field work performed by Tom Wilson in conjunction with Dr. Shane Cronin at Massey University and Mt. Ruapehu;
3) Consultation with experts in the field in New Zealand, Indonesia, and elsewhere
4) Literature review of published research on similar tephra impacts on crops at other volcanoes

The fragility functions in this science report are thus primarily meant to establish a “first-order” departing point from which future researchers can adapt the given functions or build new, more refined functions based on additional ground-truthed and/or laboratory-based observations of volcanic damage to agricultural items. Clearly, the functions should be used with an appropriate degree of care, and will improve over time as they are modified as more is learned from eruptions about tephra impacts to crops.

10. PUBLICATION III – WIND STATISTICS

<u>"Examining wind patterns above the central North Island for tephra dispersion modeling with ASHFALL in RiskScape"</u>

GNS Science Report (2007/36)
By Grant Kaye
41 pages
ISSN 1177-2425
ISBN 978-0-478-19602-3

10.1 Corrections and Additions to Publication

10.1.1 Long-term Weather Phenomena – El Niño and La Niña.

This Science Report does not contain any comment on the potential influence of long-term weather phenomena, particularly El Niño and La Niña southern oscillations. A brief discussion of these weather patterns and their influence on New Zealand will be given here.

During an El Niño, the weather in New Zealand generally tends to be driven by stronger, more frequent westerly winds in the summertime, leading to dry conditions along the east coasts of the North and South Islands and moist conditions on the opposite shores (Kidson and Renwick, 2002). If this is the case and an eruption occurs during an El Niño year, then there would be an elevated chance of any erupted tephra from (for example) the OVC being carried to the east away from Rotorua during a summertime eruption. Wintertime winds during El Nino conditions trend towards southerly, causing colder air and ocean temperatures, and spring and summer winds tend to be southwesterly, ushering in a mixture of cold and warm conditions (NIWA, 2008). In this case, an El Niño wintertime eruption from the OVC would carry tephra to the north and the cities of Tauranga and potentially Hamilton in the Bay of Plenty. Also, periods of prolonged drought along the East Coast occur both during El Niño years (1997-1998; Basher, 1998) and non El Niño years (1988-1989; NIWA, 2008), which by analogue would decrease the threat of post-eruption lahars occurring as a result of heavy rainfall events onto freshly deposited volcanic material. Despite El Niño's potential to have a strong influence on weather in New Zealand, it accounts for less than 25% of annual fluctuation of precipitation and temperature variations (Mullan, 1996).

In times of a pacific La Niña pattern such as 2007/2008, New Zealand weather is impacted more weakly than during El Niño but tends to consist of more prevalent northeasterly winds (NIWA, 2008). Also during La Niña years, rainfall amounts are generally higher, making most of the country wetter (Zheng and Frederikson, 2006). Following the above example of a tephra-producing eruption from the

OVC during a La Nina, tephra would be carried by prevailing winds as dictated in the science report, but might have an elevated probability of being carried to the southwest by northeasterlies, impacting Taupo and potentially Wanagnui and the Taranaki region. Furthermore, wetter conditions could elevate lahar hazards during a La Nina.

In terms of forecasting winds and thus tephra dispersion patterns above the North Island during an El Niño versus La Niña, Zheng and Frederiksen (2006) reiterate the point made in the conclusion of this science report that accurate prediction of day-to-day weather variability over periods of time longer than the typical prediction period (10 days) is not reliably possible in the extratropics (e.g. New Zealand). Bonadonna et al. (2005) concluded that El Niño and La Niña fluctuations would not impact the dispersal of tephra from a modelled Tarawera eruption.

10.1.2 Difference Between Modelled and Observed Wind Speeds.

In this Science Report, references are made to both “modelled” and “observed” wind speeds. Here, a brief comment will be provided here regarding the difference between the velocities of these two datasets.

Observed wind speeds are physically recorded wind speeds measured by radiosonde balloons or by anemometers at meteorological stations. Chapter 1 of this Science Report gives a description of locations where wind direction and velocity measurements are made, such as Rotorua or Hamilton. Modelled wind speeds (windrun files) are predictions resulting from computer-model based averages of observations made at Whenuapai (near Auckland), and Paraparaumu (near Wellington).

A discrepancy exists between the velocities of observed wind speeds at Hamilton and modelled wind speeds at various locations around the North Island (reported in Figures 3.21- 3.24), with the Hamilton observations being anywhere from ~10 m/s slower at the ground surface to ~30-40 m/s slower at ~9,000 above sea level. Both sets of data exhibit a positively correlated increase in velocity with elevation. The higher velocities of the windrun modelled data are presumably an artefact of the averaging used by the computer models to generate the windrun forecasts for the various locations around the North Island from observations made at Whenuapai and Paraparaumu (which is presumably more likely to have higher velocity winds than Whenuapai). In the future, wind forecasting above New Zealand volcanoes will hopefully be improved as additional observations are collected in the upper atmosphere at more locations, and observations can replace modelled data.

10.2 References in this Addendum

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11. PUBLICATION IV – RISKSCAPE VOLCANO MODEL

‘RiskScape Volcano – a volcanic hazard risk assessment model for RiskScape”

GNS Science Report (2007/38)
By Grant Kaye

227 pages
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11.1 Corrections and Additions to Publication

The reference “Heydenrych et al., 2005” is missing from the references, it is:

Heydenrych, C., Cudmore, R., Gimson, N., Revell, M., Fischer, G., and Zawar-Reza, P., 2005. CALPUFF model validation in New Zealand: methodology and issues. Kingett Mitchell Limited, Auckland, 15 p.

11.1.1 Uncertainty of Hazard Models in Table 3.2

Table 3.2 in this Science Report does not discuss uncertainty in the models estimates. What follows is an addendum to the table with a brief comment on uncertainty for each model where the models’ original authors or end-users explicitly discussed uncertainty in their publications. Not all models in Table 3.2 are presented. Sources of both models and application examples are given in the original table in the Science Report.

Model	Uncertainty
Trusdell / Kauaihikaua Lava Flow	Uncertainty increases as flow decreases, especially high in areas where slope is less than 5%. Also, lava flows can change topography, making DEM invalid. Quality of the DEM resolution also impacts uncertainty, thus uncertainty in the X-Y dimension can also be estimated as 1 to possibly 2 times the elevation value of the DEM (e.g. 25 m DEMs for New Zealand = 25 to 50 m horizontal uncertainty)
MAGFLOW	Uncertainties in model results are correlated to both topographic uncertainties and flow rate uncertainties
DOWNFLOW	Larger uncertainties in elevation model require more significant stochastic variation on topography. Vertical error of less than a few meters means stochastic perturbation roughly equals the vertical characteristic length of the lava flow being modelled.
LAHARZ	Extent of proximal hazard zones delineated with low uncertainty. Roughly a two-order-of-magnitude range in lahar volume correlated to a two-order-of-magnitude range in recurrence interval, see Figure 11 in Iverson et al (1998) for graphical depiction of uncertainty.
TITAN-2D	Not explicitly discussed, uncertainty stems from DEM resolution and parameters of volume and viscosity, interaction with underlying substrate
RSV Seiche Model	1-2 times the vertical DEM resolution in the X-Y direction
ASHFALL	Mostly dependent upon the wind direction and velocity parameters in the atmospheric model as well as the grain size distribution parameters used to model the eruption column.
TEPHRA	Not explicitly discussed, results depend upon wind parameters used and level of understanding of grain size distribution in eruptive column
HAZMAP	Not explicitly discussed
EJECT!	~1 m X-Y distance, ~1-2 m/s velocity, and 0.01 sec time for estimating ejection trajectory of spheres. Uncertainties involved with use in modeling actual volcanic materials can be substantial, based on uncertainties in ejection angle, velocity, and atmospheric conditions.
EXPLORIS-PDC	Velocity to within 3 m/s, PDC extent within hazard maps of at least 0.8 km horizontal scale. Also, number of PDC pulses impacts eventual certainty of output.
FLOW3D	PDC distances range from 2-3 km (from use of model in Saucedo et al., 2005)
ALOHA	Dashed lines around predictions, see figure 3.14, depends upon wind direction and velocity and atmospheric conditions.
CALPUFF	Not explicitly discussed in Heydenrych et al., 2005
NZ Earthquake Model	Not explicitly defined, model still in development

Table 11.1 Uncertainties of hazard models from Table 3.2 in Publication IV, if explicitly discussed.

11.1.2 PDC Density Parameter Value

This publication incorrectly cites the average density value of the PDCs discussed in Clarke and Voight (2000) as 4,100 kg/m^3; the density reported in that paper is actually 4.1 kg/m^3. This value from their paper is meant to represent the overall average density of the entire PDC, including the ash, gas, and solid material. The density is "low" because it accommodates the density of the gas part of the PDC. Preliminary modeling with EXPLORIS-PDC model of Toyos et al. (2007) attempted to use this "low" value, however, the model returned unusable results in the form of negligible dynamic overpressure values that were thus unusable in risk assessments. The Toyos model does not output reasonable kPa values (reasonable in that the values are near those given by Clark and Voight in their 2000 paper from field calculations of damaged objects) until PDC densities in the 1000s of kg/m^3 are used. That is why a value of 4,100 kg/m^3 was cited and used originally in this publication as well as publications V and VI; the density parameter value was chosen by starting from the Clark and Voight 2000 average figure and adjusting the order of magnitude to the thousands of kg/m^3.

The initial comments of the examiners of this thesis led the author to re-examine the chosen value of the PDC density parameter, primarily to see if a more specific value could be chosen following a re-examination of Toyos et al. (2007), and if so, to determine if the model would need to be re-run and would subsequently change any of the risk assessment results in Publications V and VI. Several attempts were made in July and August 2008 to contact Paul Cole (one of the authors of the model) to specifically inquire about what density he would suggest to use with his model, but it was not possible to reach him. Unfortunately, his paper does not specifically discuss the nature of the source of the density parameter (is it meant to be the density of the solid phase of the flow, or the average density of gas + solid? This is not discussed explicitly). It was discovered, however, that one of the figures in Toyos et al. (2007) has the density value filled in at 1,300 kg/m^3. Thus, future use of the EXPLORIS-PDC model should utilize a value of 1,300 kg/m^3 until more information is obtained from the models' authors. Discussion of the need to re-run the model for the Rotorua risk assessment of publication V is found in Chapter 12, below.

12. PUBLICATION V – ROTORUA RISK ASSESSMENT

"Risk assessment for population, agriculture, and infrastructure in the Rotorua District from a rhyolite eruption at the Okataina Volcanic Centre, New Zealand"

GNS Science Report (2007/39)
By Grant Kaye
62 pages

ISSN 1177-2425
ISBN 978-0-478-19605-4

12.1 Corrections to publication

- p. 31 – Table 3.4 – density should be given as kg/l, where "l" = litres.
- p.52, section 8.2 – Schilling et al., 1988 is an incorrect citation – the correct citation is Iverson et al., 1988:

  Iverson, R.M., Schilling, S.P., and Vallance, J.W., 1988. Objective delineation of lahar-inundation hazard zones. GSA Bulletin, v. 110, no. 8, p. 972-984.
- Estimated flow parameters for comparison to the 1305 a.d. Kaharoa eruption (Section 7.3) are:
  - Volume = 5 km^3 (total eruption; Nairn, 2002)
  - Column height = ~25 km (Bonadonna et al., 2005)

12.2 EXPLORIS-PDC Density Parameter Value

As discussed in section 11.3 above, Publication IV proposed a value for the density used in PDC modeling with the Toyos et al (2007) EXPLORIS model that was too high. The question then arose as to whether or not the PDC modeling done in the Rotorua risk assessment needed to be re-run with the lower density value of 1,300 kg/m^3. After re-running the model with the lower density it was determined that the lower value does not impact the risk assessment results, within the rounding error (Figure 12.1). The resultant dynamic pressures using the 1,300 kg/m^3 density value are still significant and thus sufficient to cause the same amounts of damage as that done if the density was 4,100 kg/m^3 across all inventory classes. Further, lowering the density parameter does not at all impact or change the modelled velocity or extent of the flows (a.k.a. their "footprint"; e.g. Figure 3.6 in publication IV) due to the way the Toyos model translates the volume of the PDC over the DEM into the flow's mapped extent.

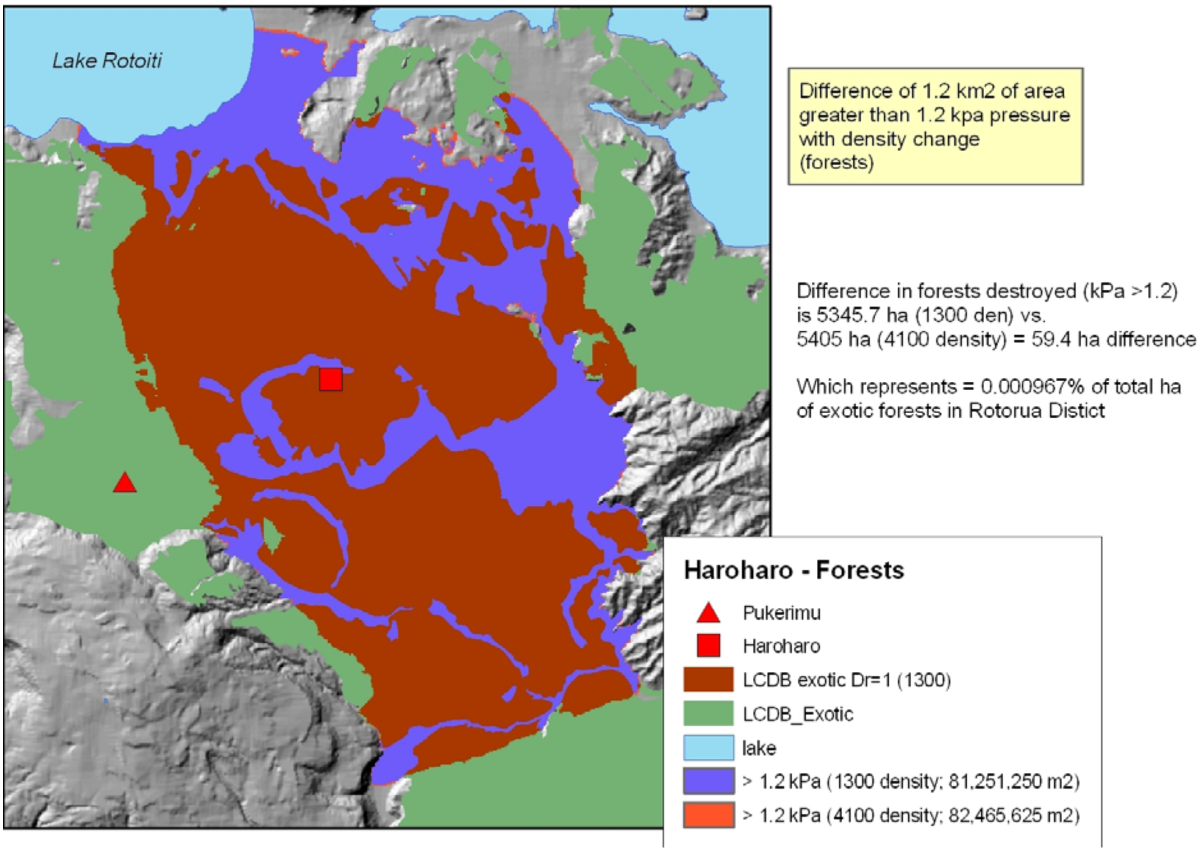

Figure 12.1 Differences in destroyed forests (brown; $D_r > 1$ where kPa > 1.2) from two model runs of EXPLORIS-PDC: a first with a density of 1300 kg/m^3 (purple) and a second using a density of 4100 kg/m^3 (orange, visible at limits of purple shading).

Figure 12.1 shows results from two different model runs of EXPLORIS-PDC, using the same flow source and volume and both low and high density parameter values. The purple shading shows the area where the overpressure exceeds 1.2 kPa (D_r for exotic forest = 1) with a density of 1,300 kg/m^3. The underlying orange area (visible at the outer fringes of the purple area) shows locations where the kPa is >1.2 with a density of 4,100 kg/m^3. The orange area extends roughly 50 m outwards further than the purple area around its edges. As described in the yellow box to the right of Figure 12.1, the area where the PDC overpressure exceeds 1.2 kPa with EXPLORIS-PDC using a density of 4,100 kg/m^3 exceeds the area where the overpressure exceeds that same value using a density of 1,300 kg/m^3 by only 1.2 km^2. In terms of destroyed forests (shown in brown in Figure 12.1 for the 1300 kg/m^3 density model run only), this represents 5,345 ha destroyed with EXPLORIS-PDC using a density of 1,300 kg/m^3 versus 5,405 ha with the model using a 4,100 kg/m^3 density - a difference of 59.4 ha, or 0.000967% of the total area of forests in the Rotorua District. This small amount is within the rounding used to provide the risk assessment results in Publication V (e.g. Table 10), and thus re-running the PDC model for all risk assessments is unnecessary, as the lower density value does not change the results.

13. PUBLICATION VI – MAMMOTH RISK ASSESSMENT

“Comparison of pyroclastic density current hazard risk to critical infrastructure in Mammoth Lakes, California, USA from a new Inyo craters rhyolite dike eruption versus a dacitic dome eruption on Mammoth Mountain”

Manuscript as accepted by *Natural Hazards*
24 October 2008

By Grant Kaye, Jim Cole, Andrew King, and David Johnston

28 pages

13.1 Specific Contributions of Mr. Kaye to the Manuscript

The report was authored entirely by Mr. Kaye. The other authors’ names are present to recognize their roles as the PhD advisor (Jim Cole) and committee members (Andrew King and David Johnston), as is typically the custom with journal papers authored by PhD candidates. The other authors provided much useful discussion and editing, but did not make any specific contributions to the actual preparation of the report.

13.2 EXPLORIS-PDC Density Parameter Value

The version of this publication that was accepted for publication by *Natural Hazards* on 24 October 2008 contains model results that used a density value of 1,300 kg/m^3, as discussed above in Section 11.3. In a similar fashion to the discussion of the lack of a need to change the risk assessment results in Publication V (Rotorua risk assessment) in section 12.2 above, the risk assessment results in this publication were unchanged from earlier versions of the manuscript which used a density parameter value of 4,100 kg/m^3. Table 13.1 shows the different overpressures at the critical infrastructure locations as a result of both density values bring used in the modeling. This produces overpressures that are markedly lower when EXPLORIS-PDC is run with the lower density value; however the values are still high enough to cause the same D_r.

Item	Class	Mammoth Mtn. Dacite Dome 10^7 m^3 (p = 4100 kg/m^3)			Mammoth Mtn. Dacite Dome 10^7 m^3 (p = 1300 kg/m^3)		
		Dynamic Pressure (kPa)	Velocity	D_r	Dynamic Pressure	Velocity	D_r
Intrawest Village	Lodge	57.3	5.3	1	18.2	5.3	1
Main Ski Area Base Lodges	Lodge	303.2	12.2	1	96.1	12.2	1
Canyon Lodge	Lodge	456.6	14.9	1	144.8	14.9	1
Tamarack Lodge	Lodge	382.9	13.7	1	121.4	13.7	1
Eagle Lodge	Lodge	418.87	14.3	1	132.8	14.3	1
Fire Station 2	Police/Fire/Hospital	95.5	6.8	1	30.3	6.8	1
Police Headquarters	Police/Fire/Hospital	0	0	0	0	0	0
Mammoth Hospital	Police/Fire/Hospital	0	0	0	0	0	0
Fire Station 1	Police/Fire/Hospital	0	0	0	0	0	0
Mammoth High School	School	0	0	0	0	0	0
Cerro Coso Community College	School	0	0	0	0	0	0
Mammoth Elementary School	School	33.62	4.1	1	10.7	4.1	1
Mammoth Middle School	School	0	0	0	0	0	0
Ski Area Electrical Substation	Utility	291.66	11.9	1	92.5	11.9	1
Edison Office and Substation	Utility	0	0	0	0	0	0
Mammoth Community Water District	Utility	0	0	0	0	0	0
Verizon Station and Cell Tower	Utility	0	0	0	0	0	0
Mammoth Public Works	Utility	0	0	0	0	0	0
Turner Propane	Utility	0	0	0	0	0	0
AmeriGas		0	0	0	0	0	0

Table 13.1 Comparison of results for Mammoth Mountain 10^7 m^3 PDC with densities of 4,100 kg/m^3 versus 1300 kg/m^3.

14. PUBLICATION VII – MAMMOTH HAZARD AWARENESS SURVEY

“Volcanic hazard awareness in the tourism sector in Mammoth Lakes, California, USA”

GNS Science Report (2008/35)
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10 pages

14.1 Specific Contributions of Mr. Kaye to the Manuscript

The majority of the paper was authored by Mr. Kaye, including all of Sections 1, 2, and 3, and most of Sections 4, 5, and 6. Dr. Johnston and Mr. Kaye worked together to re-write and edit the paper throughout its development. Dr. Johnston and Dr. Paton contributed references and some text in Sections 4 and 5 with regard to their expertise in hazards psychology, and Dr. Johnston and Dr. Finnis performed the initial data entry into the SPSS software and subsequent statistical analysis of the survey data to generate Table 1.